

For a better understanding of the operating point of high power tetrodes

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Table of Symbols

P	RF Output Power
η	Anode Efficiency
V_{A_c}	dc Anode voltage
$I_{a_{av}}$	Average Anode current
$V_{a_{rmspeak}}$	Peak RF Anode Voltage
$I_{a_{rmspeak}}$	Peak RF Anode current
$V_{g_{rmspeak}}$	Peak RF control grid voltage
G	Gain
I_P	Peak Current delivered by the tetrode
θ_0	Half conduction angle
F	Operating Frequency
V_r	Remaining voltage
I_{G_2}	Screen Grid current
P_d	Dissipated Power
VSWR	Voltage Stationary Wave Ratio
R_T	Load resistance on the tube for VSWR = 1
Z_T	Load impedance on the tube
γ	Reflection coefficient
$ \gamma $	Module of the reflection coefficient
φ	Phase of the reflection coefficient
Σ	Chain Matrix of a two-port device

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1 Introduction

The aim of this document is to provide the designer of a high power tetrode based amplifier with the full set of parameters and equations in order to properly define his system.

High power tetrodes have impressive capabilities but also limitations: it is fundamental to show these capabilities but it is even more essential to address the different limits in the use of this technology.

The second objective is to show the possibilities to extend the properties of tetrodes by the use of double-ended solutions in order to increase pulse duration up to cw operation, or to increase the full performance frequency range or to allow higher VSWR values. These double-ended tetrodes are known as Diacrodes, a technology developed by Thales for use in the TV broadcast domain, both for analogue and digital applications. This technology has been used for years.

Starting with a very simple model, the first part of this paper will introduce the reader with the fundamentals of tube load to understand how it acts on all the parameters of a tetrode: these parameters are called operating points (RF output power, dissipated power, gain, efficiency, dc anode voltage, screen grid current).

The second part will introduce the effect of the reflection coefficient (VSWR any phase) on the load of the tube and the effect on the operating points and, therefore, on the performances of a RF amplifier based on tetrodes.

The third and fourth part will show the influence on tetrode linked to frequency, mainly for long pulse operation, up to cw operation, and the consequences on the performance.

Customers and factory results will be presented for short and long pulse operation.

The fifth part will describe the Diacrode technology, a double-ended tetrode: it will also show how this technology can push away the limitation in performance of conventional tetrodes.

Any designer of a high power tetrode based amplifier will find here all the equations in order to apply them to his particular situation and then, define the best choice.

2 Operating points of tetrodes

2.1 Definition of the operating point

The so called operating point defines all the electrical parameters of a tetrode for a given performance.

These parameters are the RF output power, all the currents (anode, screen grid, and control grid), all the dc voltages (anode, screen grid, and control grid), the gain, the anode efficiency and the frequency. The values of these parameters are function of the size and the constant characteristics curves of the tube. For more clarity, we will assume that the size of the tube is small compared to the wavelength and, therefore, that the frequency has no effect on the operating point. The effect of the frequency on the behavior of the tetrode will be described in Paragraph 4

2.2 Efficiency

Assume that the required performances are the RF power P and an efficiency η , with a dc anode voltage VA_c .

One has to estimate the parameter for the constant characteristics curve.

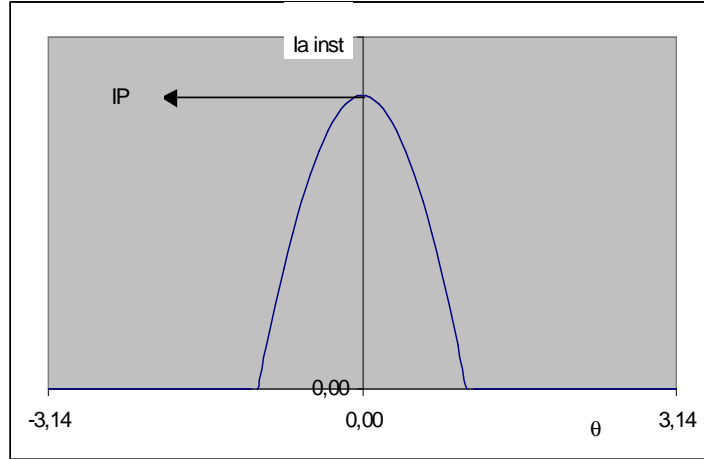
The efficiency η can be written as :

$$\eta = \frac{P}{VA_c * Ia_{av}} = \frac{Va_{rmspeak} * Ia_{rmspeak}}{2 * VA_c * Ia_{av}} \quad (1)$$

According to the operating class of the amplifier,

Class A	$\theta_0 = \pi$
Class AB	$\theta_0 \in \left\langle \frac{\pi}{2}, \pi \right\rangle$
Class B	$\theta_0 = \frac{\pi}{2}$
Class C	$\theta_0 < \frac{\pi}{2}$

Figure 1



The shape of the current in a tetrode is as shown on Figure 1.

The average and RF peak anode current are derived, using Fourier's series :

The instantaneous anode current is defined by equation 2

$$Ia(\theta) = \frac{IP * (\cos(\theta) - \cos(\theta_0))}{1 - \cos(\theta_0)} \quad (2) \quad \text{where} \quad \theta = \omega * t = 2 * \pi * F * t$$

The signal being symmetrical the average current and the peak RF current are given by equations 3 and 4 and the Fourier's coefficients $f(\theta_0)$ and $g(\theta_0)$, by equations 5 and 6.

$$Ia_{av} = IP * f(\theta_0) \quad (3)$$

$$Ia_{rms\ peak} = IP * g(\theta_0) \quad (4)$$

$$f(\theta_0) = \frac{\sin(\theta_0) - \theta_0 * \cos(\theta_0)}{\pi * (1 - \cos(\theta_0))} \quad (5)$$

$$g(\theta_0) = \frac{2 * \theta_0 - \sin(2 * \theta_0)}{2 * \pi * (1 - \cos(\theta_0))} \quad (6)$$

Then, with equation 1, the efficiency and the peak RF anode voltage can be derived:

$$\eta = \frac{Va_{rmspeak}}{4 * VA_c} * \frac{2 * \theta_0 - \sin(2 * \theta_0)}{\sin(\theta_0) - \theta_0 * \cos(\theta_0)} \quad (7)$$

$$\Leftrightarrow Va_{rmspeak} = \eta * VA_c * 4 * \frac{\sin(\theta_0) - \theta_0 * \cos(\theta_0)}{2 * \theta_0 - \sin(2 * \theta_0)} \quad (8)$$

Equation 8 allows for a quick estimation of the RF anode voltage.

If the tube operates in Class B

$$\theta_0 = \frac{\pi}{2} \quad (\text{Class B}), \quad \text{then} \quad \eta = \frac{V_{a_{rmspeak}}}{V_{A_c}} * \frac{\pi}{4} \quad \Leftrightarrow \quad V_{a_{rmspeak}} = \eta * V_{A_c} * \frac{4}{\pi}$$

With a resonant circuit the instantaneous RF anode voltage is a sine wave.

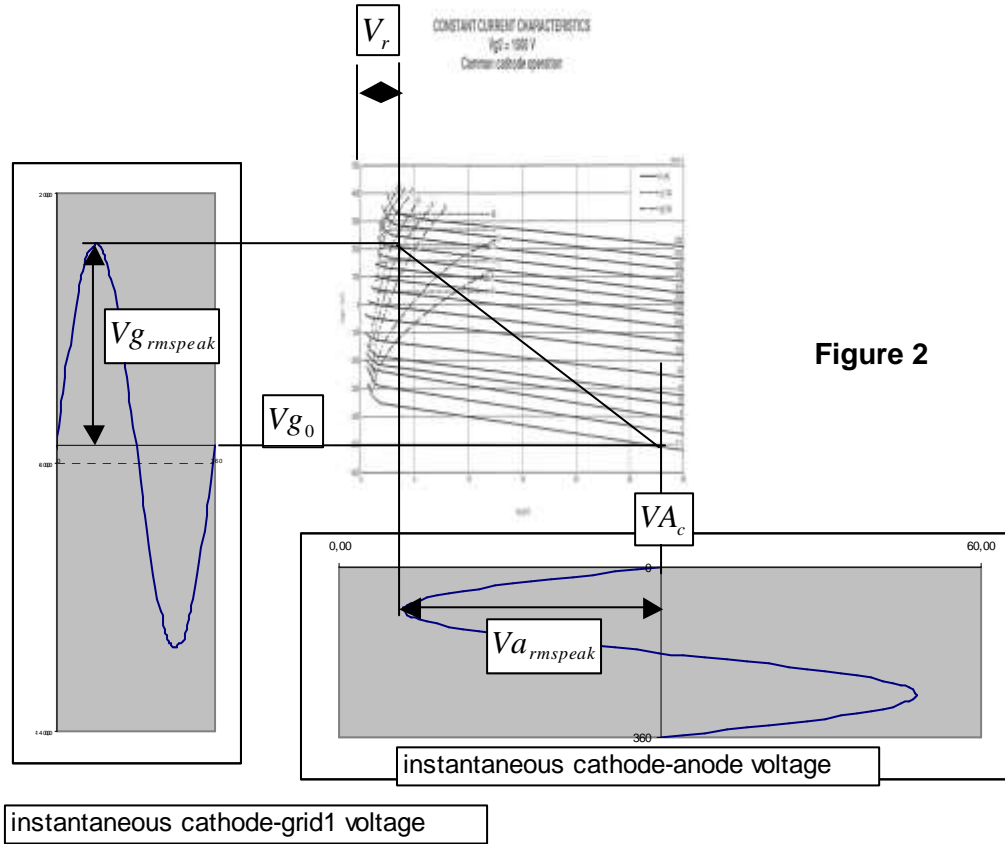


Figure 2

Let us introduce the remaining voltage V_r , defined as $V_r = V_{A_c} - V_{a_{rmspeak}}$ (9)

Then,

$$\eta = \left(1 - \frac{V_r}{V_{A_c}}\right) * \frac{2 * \theta_0 - \sin(2 * \theta_0)}{2 * (\sin(\theta_0) - \theta_0 * \cos(\theta_0))} \quad (10)$$

The efficiency is a function of the operating class, the continuous anode voltage and the remaining voltage.

We will see later on how important is the remaining voltage and how to choose it.

With a given operating class θ_0 , a power P , a dc anode voltage V_{A_c} , a remaining voltage V_r , by using equation (10), one can estimate the efficiency and by using equations (8) and (3), estimate the peak anode current IP .

The constant characteristics curve therefore gives the dc control grid voltage and IP gives the peak value of the control grid voltage. So one can draw a line between the points $A(V_{g_0}, V_{A_c})$ and $B(V_{g_{peak}}, V_r)$. This line defines the voltage gain and allows to compute the

instantaneous anode current. We will stop here this calculation with the constant characteristics curve, which presents no difficulty and move on with the load of the tube, which is more important.

2.3 Remaining voltage

$$V_r = V_{A_c} - V_{a_{rmspeak}}$$

The value of the remaining voltage is strongly dependent of the screen grid current. This can be understood by the constant characteristics curve, IG2 as a function of V_{g1} , for different anode voltages.

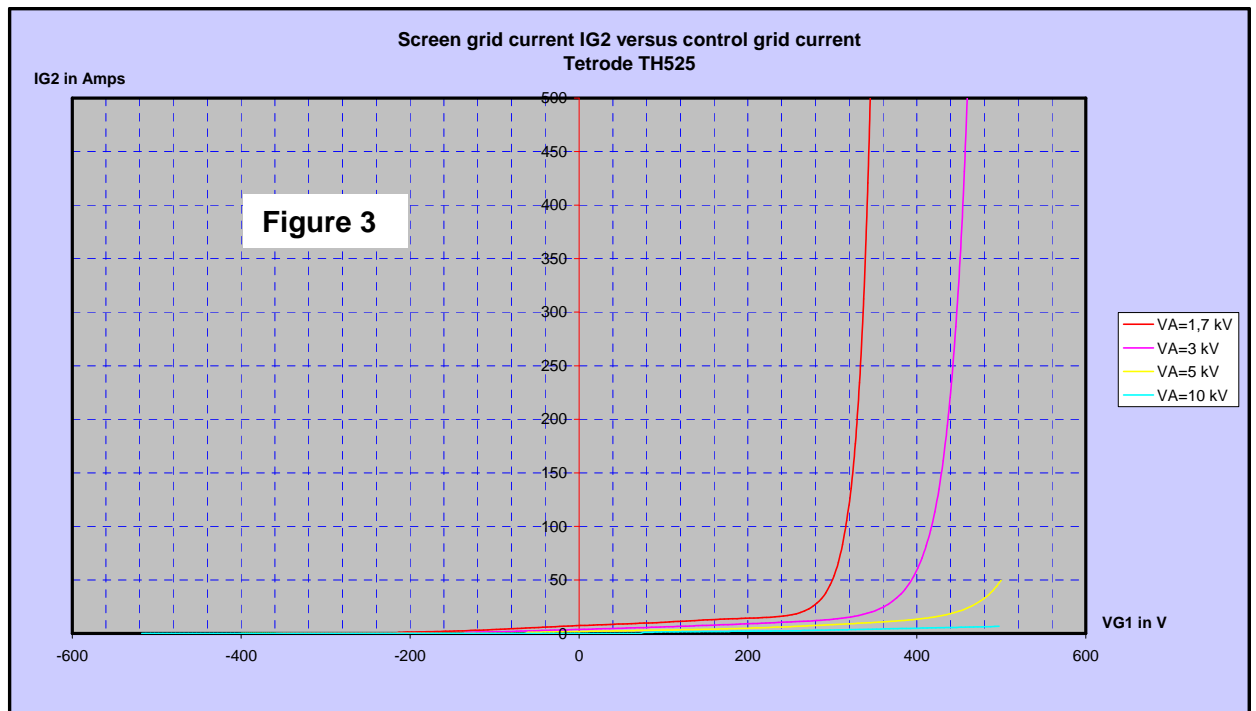


Figure 3 shows that the screen grid current reaches very high values for low anode voltages and high control grid voltages. This curve explains the phenomenon of saturation observed on tetrodes when one wants to increase the output power (i.e. RF control grid voltage) without increasing the continuous anode voltage.

Looking at the value of the screen grid current for $V_{g_{peak}} = 400V$, $1.7kV < V_a = V_r < 3kV$, the screen grid current increases drastically. It means that the electron flow coming from the cathode is intercepted by the grids and mainly by Grid 2: the number of electrons reaching the anode decreases, as the RF power.

This is why the remaining voltage is so important and its value must be chosen very carefully. For example, for the TH525 Thales tetrode, the average screen grid current must be limited at 4.5 to 5 A.

2.4 Load resistance

In the previous paragraph, the anode RF voltage and current have been defined.

$$Va_{rmspeak} = \eta * VA_c * 4 * \frac{\sin(\theta_0) - \theta_0 * \cos(\theta_0)}{2 * \theta_0 - \sin(\theta_0)} \quad Ia_{rmspeak} = IP * g(\theta_0)$$

With these two equations, a load resistance can be defined.

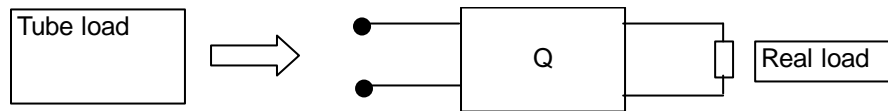
$$R_{load} = \frac{Va_{rmspeak}}{Ia_{rmspeak}} \quad (11)$$

and the expression of the RF power can be derived as below.

$$P = \frac{Va_{rmspeak} * Ia_{rmspeak}}{2} = \frac{Va_{rmspeak}^2}{2 * R_{load}} = R_{load} * \frac{Ia_{rmspeak}^2}{2} \quad (12)$$

The load resistance is a specific parameter of a tetrode completely determined by the constant characteristics curve.

When a tetrode is used to a real load (antenna, dummy load, etc.), the circuit around the tetrode (RF circuit) acts as a two-port device in order to convert the real load into the tetrode load.



Example of a circuit

The real load is $R_{realload} = 50\Omega$

The tetrode requires, for example

$$R_{tubeload} = 100\Omega$$

Then the device must be defined as in Annex 11.

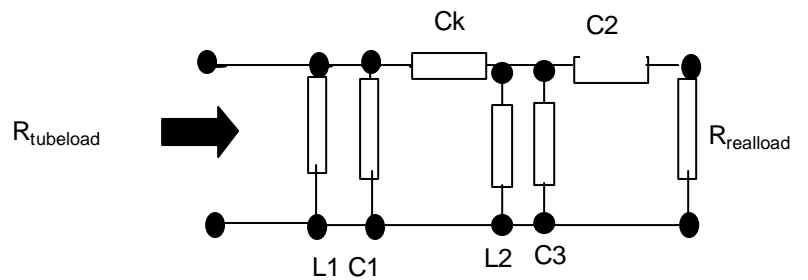


Figure 4
Example of a tunable transformer

As it is well known, the bandwidth of the circuit is determined by the value of $R_{realload}$ and the value of the reactive components

2.5 Determination of the highest and lowest load for a given constant characteristics curve

We have seen in the previous paragraph (i) how to choose the minimum remaining voltage and (ii) on the constant characteristics curve, that there is a curve, which gives the highest current, called here IP_{\max} . In the following calculations, we assume to have a given dc anode voltage VA_c , a RF power P , a class of operation θ_0 and a remaining voltage V_r

2.5.1 Highest load resistance

From equations (9) and (12), one can derive the highest load resistance:

$$Va_{rmspeak} = VA_c - V_r \quad (13)$$

$$RT_{high} = \frac{Va_{rmspeak}^2}{2 * P} \quad (14)$$

2.5.2 Lowest load resistance

From equations (4) and (12), the lowest load resistance is:

$$RT_{Low} = \frac{2 * P}{IP_{\max}^2 * g(\theta_0)^2} \quad (15)$$

It is obvious that if $RT_{High} < RT_{low}$ the value of P is wrong

The load of the tube to stay inside the constant characteristics curve must be in the range of :

$$RT_{Low} \leq RT \leq RT_{High}$$

This quick calculation is very helpful to estimate which value of the load is compatible with the constant characteristics curve..

From equations (14) and (15), the parameter H can be defined.

$$H = \sqrt{\frac{RT_{High}}{RT_{Low}}} \quad (16)$$

We will see later on how to use this parameter when the tetrode is working on a VSWR.

Example of the TH 525 Thales Tetrode

$$VA_c = 27kV, IP_{\max} = 550A, \theta_0 = \frac{\pi}{2}, V_r = 3kV$$

$$P = 2.5MW \quad RT_{High} = 115.2Ohm \quad RT_{Low} = 66.12Ohm \quad H = 1.32$$

$$P = 1.7MW \quad RT_{High} = 169.4Ohm \quad RT_{Low} = 44.96Ohm \quad H = 1.94$$

2.5.3 Comments

Let's assume that a tube is in operation at a given power. What happens if the RF circuit is tuned to increase the load of the tube. The value of the coil and the capacitance are changing (see Annex 11).

Let R_{l1} be the load with the first tuning and R_{l2} , the load when the tuning has been changed.

So: $R_{l1} < R_{l2}$

The dc voltages are constant, the input power also and the tube is not at saturation.

At the first order, the input power being constant, the RF anode peak current does not change.

Therefore :

RF power

$$P(R_{l1}) = R_{l1} * \frac{Ia_{rmspeak}^2}{2} \quad \text{becomes} \quad P(R_{l2}) = R_{l2} * \frac{Ia_{rmspeak}^2}{2}$$

with $P(R_{l2}) > P(R_{l1})$

Increasing the load does increase the RF power.

RF Voltage

$$Va_{rmspeak}(R_{l1}) = R_{l1} * Ia_{rmspeak} \quad \text{becomes} \quad Va_{rmspeak}(R_{l2}) = R_{l2} * Ia_{rmspeak}$$

with $Va_{rmspeak}(R_{l2}) > Va_{rmspeak}(R_{l1})$

Increasing the load does increase the RF peak anode voltage.

Gain

In a common grid configuration, at the first order (lg1 and lg2 are not taken into account),

the Gain is defined by $G = \frac{Va_{rmspeak}}{Vg_{rmspeak}}$

$$G(R_{l1}) = \frac{Va_{rmspeak}(R_{l1})}{Vg_{rmspeak}} \quad \text{becomes} \quad G(R_{l2}) = \frac{Va_{rmspeak}(R_{l2})}{Vg_{rmspeak}}$$

with $G(R_{l2}) > G(R_{l1})$

Increasing the load does increase the Gain.

Remaining voltage

$$Vr(R_{l1}) = VA_c - Va_{rmspeak}(R_{l1}) \quad \text{becomes} \quad Vr(R_{l2}) = VA_c - Va_{rmspeak}(R_{l2})$$

with $Vr(R_{l2}) < Vr(R_{l1})$

Increasing the load does decrease the remaining voltage.

Screen grid current

In the previous paragraph, we have seen that the lowest is the remaining voltage the highest is the screen grid current ($IG2$).

$$IG2(R_{l2}) > IG2(R_{l1})$$

Increasing the load does increase the screen grid current.

Dissipated power

$$Pd = VA_c * Ia_{av} - P = VA_c * Ia_{av} - \frac{Va_{rmspeak} * Ia_{rmspeak}}{2}$$

with (3), (4) and (12) :

$$Pd = VA_c * Ia_{av} * \left(1 - \frac{g(\theta_0)}{f(\theta_0)}\right) + Vr * Ia_{av} * \frac{g(\theta_0)}{f(\theta_0)} \quad (14)$$

$$Pd(R_{l1}) = VA_c * Ia_{av} * \left(1 - \frac{g(\theta_0)}{f(\theta_0)}\right) + Vr(R_{l1}) * Ia_{av} * \frac{g(\theta_0)}{f(\theta_0)} \text{ becomes}$$

$$Pd(R_{l2}) = VA_c * Ia_{av} * \left(1 - \frac{g(\theta_0)}{f(\theta_0)}\right) + Vr(R_{l2}) * Ia_{av} * \frac{g(\theta_0)}{f(\theta_0)}$$

with $Pd(R_{l2}) < Pd(R_{l1})$ because $V_r(R_{l2}) < V_r(R_{l1})$

Increasing the load does increase the dissipated power.

Efficiency

With (10)

$$\eta(R_{l1}) = \left(1 - \frac{Vr(R_{l1})}{VA_c}\right) * \frac{2 * \theta_0 - \sin(2 * \theta_0)}{4 * (\sin(\theta_0) - \theta_0 * \cos(\theta_0))} \text{ becomes}$$

$$\eta(R_{l2}) = \left(1 - \frac{Vr(R_{l2})}{VA_c}\right) * \frac{2 * \theta_0 - \sin(2 * \theta_0)}{4 * (\sin(\theta_0) - \theta_0 * \cos(\theta_0))}$$

With $\eta(R_{l2}) > \eta(R_{l1})$

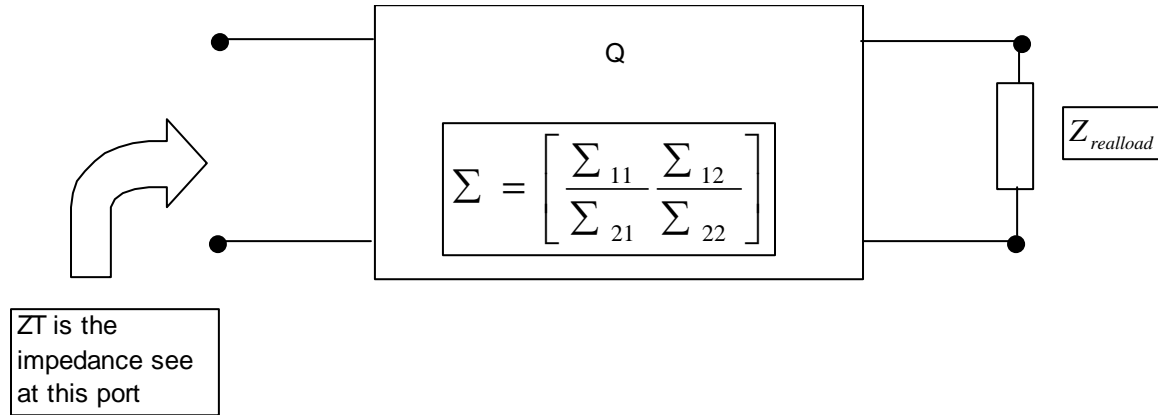
Increasing the load does increase the anode efficiency.

All the above analysis shows the importance of the tube load on the operating point and the influence on all the other parameters. The well understanding of this notion of tube load is very helpful to understand the behavior of tetrodes.

For example, if the screen grid current is too high. It means that the remaining voltage is too low. Therefore, according to the above analysis, there are two options to improve the situation: (i) to increase the dc anode voltage or (ii) to decrease the load impedance with the consequence on the other parameters as described above.

3 Reflection coefficient influence on the tube load

3.1 Reflection coefficient



Assuming that when the real load is perfectly matched ($VSWR=1$), the real load is equivalent to a resistance: $Z_{realload} = R_{realload}$ and when the two-port is loaded with this resistance, that the impedance seen at the output of this one (generator side) is also a resistance: $ZT = RT$, then the reflection coefficient on the real load side is defined as:

$$\gamma_1 = \frac{Z_{realload} - R_{realload}}{Z_{realload} + R_{realload}} \quad (17)$$

The reflection coefficient on the generator side is defined as:

$$\gamma_2 = \frac{ZT - RT}{ZT + RT} \quad (18)$$

With a two-port circuit without active elements and without losses, the module of the reflection coefficient is constant.

If $|\gamma|$ is the module of the reflection coefficient, $|\gamma_1| = |\gamma_2| = |\gamma|$, as shown in Annex 1. It can be written as a function of the VSWR (Voltage Stationary Wave Ratio) of the real load.

$$|\gamma| = \frac{VSWR - 1}{VSWR + 1} \quad (19)$$

Let φ be the phase of the reflection coefficient on the generator side then

$$\gamma = |\gamma| * [\cos(\varphi) + j * \sin(\varphi)] \quad (20)$$

From (18)

$$ZT = RT * \frac{1 + |\gamma| * [\cos(\varphi) + j * \sin(\varphi)]}{1 - |\gamma| * [\cos(\varphi) + j * \sin(\varphi)]} \quad (21)$$

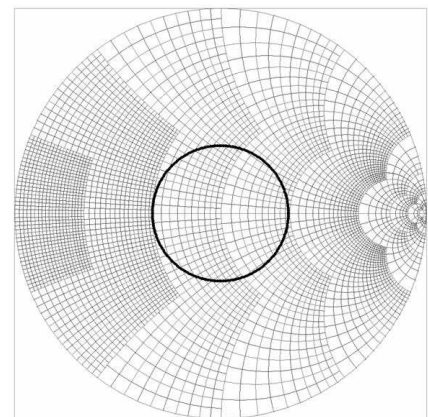


Figure 6

On Figure 6, for a $VSWR \leq 2$, the load impedance Z_T covers the entire surface of the circle.

One can also write

$$Z_T = \Re(Z_T) + j * \Im(Z_T) = R + j * X$$

where:

$$R = RT * \frac{(1 - |\gamma|^2)}{1 - 2 * |\gamma| * \cos(\varphi) + |\gamma|^2} = RT * u(|\gamma|, \varphi) \quad (22)$$

and

$$X = RT * \frac{2 * |\gamma| * \sin(\varphi)}{1 - 2 * |\gamma| * \cos(\varphi) + |\gamma|^2} = RT * v(|\gamma|, \varphi) \quad (23)$$

According to the value of φ ($\varphi \in \{0^\circ, 360^\circ\}$), some of the values are remarkable.

$$\text{For } \varphi = 0^\circ \quad R = RT * \frac{(1 - |\gamma|^2)}{(1 - 2 * |\gamma| + |\gamma|^2)} = RT * \frac{(1 + |\gamma|)}{(1 - |\gamma|)} = RT * VSWR \quad (24)$$

$$X = 0$$

Then for $\varphi = 0^\circ$ the impedance of the tube is a pure resistance and its value is the product of the resistance with $VSWR$ (RT) by the $VSWR$ of the real load.

$$\text{For } \varphi = 180^\circ \quad R = RT * \frac{(1 - |\gamma|^2)}{(1 + 2 * |\gamma| + |\gamma|^2)} = RT * \frac{(1 - |\gamma|)}{(1 + |\gamma|)} = \frac{RT}{VSWR} \quad (25)$$

$$X = 0$$

Then for $\varphi = 180^\circ$, the impedance of the tube is a pure resistance and its value is the resistance without $VSWR$ (RT) divided by the $VSWR$ of the real load.

$$\text{For } \varphi = 90^\circ \quad R = RT * \frac{(1 - |\gamma|^2)}{(1 + |\gamma|^2)}$$

$$X = RT * \frac{2 * |\gamma|}{(1 + |\gamma|^2)}$$

Then for $\varphi = 90^\circ$, the impedance of the tube is a complex value.

Let us derive, using equations (24) and (25), the following ratio:

$$h = \sqrt{\frac{ZT(\varphi = 0^\circ)}{ZT(\varphi = 180^\circ)}} = VSWR$$

A tetrode operated on a VSWR must have its constant characteristics curves compatible with the impedance defined by equations 22 and 23.

Coming back to the previous paragraph, equation (14), we know that to stay inside the constant characteristics curve, the load of the tube must stay in the range of:

$$RT_{Low} \leq RT \leq RT_{High}$$

The coefficient, $H = \sqrt{\frac{RT_{High}}{RT_{Low}}}$ has been also defined as the ratio of the highest to the lowest load resistance for a given tetrode.

A comparison between h and H shows that the maximum allowable VSWR with a given tetrode is also defined by the coefficient H . The interest of the coefficient H is to know, through a quick calculation, if a tetrode has the capability to run with a given VSWR.

If the required VSWR is greater than H , it is obvious that the considered tetrode is not usable for this application.

Note

For the moment, the limitations due to the frequency (i.e. size of the tube compared to the operating wave length) are not taken into account. We will see later on how these values are degraded.

3.2 Operating Point versus reflection coefficient

For a given VSWR, a dc anode voltage VA_c , a remaining voltage Vr_{min} for the highest load, an operating class θ_0 , and a IP_{max} from the constant characteristics curve, the power for the highest load is, based on (12), (13) and (24):

$$Va_{rmspeak} = VA_c - Vr_{min} \quad R = RT * VSWR \quad X = 0$$

$$\varphi = 0^\circ \quad P_H = \frac{Va_{rmspeak}^2}{2 * R} = \frac{Va_{rmspeak}^2}{2 * RT * VSWR}$$

The power for the lowest load is, based on equations (4), (12), (13) and (25):

$$Ia_{rms peak} = IP_{max} * g(\theta_0) \quad R = \frac{RT}{VSWR}$$

$$\varphi = 180^\circ \quad P_L = \frac{RT}{VSWR} * \frac{Ia_{rmspeak}^2}{2} = \frac{RT}{VSWR} * \frac{IP_{max}^2 * g(\theta_0)^2}{2}$$

$$\text{For } P_H = P_L = P \Leftrightarrow RT = \frac{Va_{rmspeak}}{IP_{max} * g(\theta_0)}$$

Once RT is computed, one can predict the RF power for given data such as VSWR ..

3.3 Main parameters of tetrodes operated on a given VSWR

3.3.1 Anode current

Using equations (19), (22) and (23), one can derive the anode current.

$$|\gamma| = \frac{VSWR - 1}{VSWR + 1} \quad ,$$

$$u(|\gamma|, \varphi) = \frac{(1 - |\gamma|^2)}{1 - 2 * |\gamma| * \cos(\varphi) + |\gamma|^2} \quad , \quad v(|\gamma|, \varphi) = \frac{2 * |\gamma| * \sin(\varphi)}{1 - 2 * |\gamma| * \cos(\varphi) + |\gamma|^2}$$

$$Ia_{rmspeak} = \sqrt{\frac{2 * P}{RT * u(|\gamma|, \varphi)}}$$

$$IP = \frac{Ia_{rmspeak}}{g(\theta_0)} = \frac{1}{g(\theta_0)} * \sqrt{\frac{2 * P}{RT * u(|\gamma|, \varphi)}}$$

$$Ia_{av} = \frac{Ia_{rmspeak} * f(\theta_0)}{g(\theta_0)} = \frac{f(\theta_0)}{g(\theta_0)} * \sqrt{\frac{2 * P}{RT * u(|\gamma|, \varphi)}}$$

3.3.2 RF anode peak voltage

$$Va_{rmspeak} = Ia_{rmspeak} * |ZT| = Ia_{rmspeak} * \sqrt{(RT * u(|\gamma|, \varphi)^2 + RT * v(|\gamma|, \varphi)^2)}$$

$$Va_{rmspeak} = \sqrt{\frac{2 * P * (RT * u(|\gamma|, \varphi)^2 + RT * v(|\gamma|, \varphi)^2)}{RT * u(|\gamma|, \varphi)}} \quad (26)$$

3.3.3 Remaining voltage for VA_c constant

$$Vr = VA_c - Va_{rmspeak}$$

$$V_r = V_{A_c} - \sqrt{\frac{2 * P * (RT * u(|\gamma|, \varphi)^2 + RT * v(|\gamma|, \varphi)^2)}{RT * u(|\gamma|, \varphi)}} \quad (27)$$

The remaining voltage, as mentioned in the previous paragraphs, has a large influence on the screen grid current.

3.3.4 Dissipated power

$$P_d = V_{A_c} * I_{a_{av}} - P$$

$$P_d = V_{A_c} * \frac{f(\theta_0)}{g(\theta_0)} * \sqrt{\frac{2 * P}{RT * u(|\gamma|, \varphi)}} - P \quad (28)$$

3.3.5 Efficiency

Coming back to equation (10)

$$\eta = \left(1 - \frac{V_r}{V_{A_c}}\right) * \frac{2 * \theta_0 - \sin(2 * \theta_0)}{4 * (\sin(\theta_0) - \theta_0 * \cos(\theta_0))} = \left(1 - \frac{V_r}{V_{A_c}}\right) * \frac{g(\theta_0)}{2 * f(\theta_0)}$$

$$\eta = \frac{(V_{A_c} - V_r)}{V_{A_c}} * \frac{g(\theta_0)}{f(\theta_0)} = \frac{V_{a_{rmspeak}}}{V_{A_c}} * \frac{g(\theta_0)}{2 * f(\theta_0)}$$

$$\eta = \frac{\sqrt{\frac{2 * P * (RT * u(|\gamma|, \varphi)^2 + RT * v(|\gamma|, \varphi)^2)}{RT * u(|\gamma|, \varphi)}}}{V_{A_c}} * \frac{g(\theta_0)}{2 * f(\theta_0)} \quad (29)$$

3.3.6 Comments

All the operating points of a tetrode operated on a V_{SWR} are strongly dependent of this one. For the efficiency, it is always necessary to specify the condition in which this one should be measured.

3.3.7 Example

Let assume that the tetrode is the TH525 from Thales and:

$$V_{A_c} = 27kV, IP = 550A, \theta_0 = \frac{\pi}{2}, V_{r_{min}} = 3kV, V_{SWR} = 2$$

The TH525 is a tetrode which has the capability to deliver 2 MW on $V_{SWR} \leq 1.5$, any phase, on a frequency range (35-80 MHz) with 30 second pulse and a 12.5% duty (Tore Supra, JET)

Then:

$$|\gamma| = \frac{VSWR - 1}{VSWR + 1} = \frac{1}{3}$$

$$f\left(\frac{\pi}{2}\right) = \frac{\sin\left(\frac{\pi}{2}\right) - \frac{\pi}{2} * \cos\left(\frac{\pi}{2}\right)}{\pi * (1 - \cos\left(\frac{\pi}{2}\right))} = \frac{1}{\pi}$$

$$g\left(\frac{\pi}{2}\right) = \frac{2 * \frac{\pi}{2} - \sin\left(2 * \frac{\pi}{2}\right)}{2 * \pi * (1 - \cos\left(\frac{\pi}{2}\right))} = \frac{1}{2}$$

$$Va_{rmspeak} = VA_c - Vr_{min} = 24kV$$

$$RT = \frac{Va_{rmspeak}}{IP_{max} * g\left(\frac{\pi}{2}\right)} = \frac{24E3}{550 * \frac{1}{2}} = 87.3\Omega$$

$$ZT(|\gamma| = \frac{1}{3}, \varphi = 0^\circ) = RT * VSWR = 174.5\Omega$$

$$ZT(|\gamma| = \frac{1}{3}, \varphi = 180^\circ) = \frac{RT}{VSWR} = 43.6\Omega$$

$$P = \frac{Va_{rmspeak}^2}{2 * RT * VSWR} = 1.65MW$$

Increasing the VSWR from 1.5 to 2 leads to a degradation of the performances for a given tetrode.

Once again, for the moment, the size of the tetrode, compared to the wave length, is not taken into account.

3.4 Tables of Main parameters for the TH525 with VSWR any phase.

φ in degree	u	v	ZT		I _{armspeak} A	IP A	I _{av} A	V _{armspeak} kV	P kW	Pd kW	η %	Vr kV
			Ohm	Ohm								
			R	X								
0	2,00	0,00	174,55	0,00	137,50	275,00	87,54	24,00	1650	713,45	69,81	3,00
15	1,90	0,37	166,06	32,23	140,97	281,94	89,74	23,85	1650	773,10	69,37	3,15
30	1,67	0,62	145,34	54,50	150,68	301,37	95,93	23,39	1650	940,07	68,04	3,61
45	1,39	0,74	121,27	64,31	164,96	329,92	105,02	22,64	1650	1185,49	65,87	4,36
60	1,14	0,74	99,74	64,78	181,90	363,79	115,80	21,63	1650	1476,55	62,93	5,37
75	0,95	0,69	82,65	59,88	199,81	399,63	127,21	20,39	1650	1784,55	59,32	6,61
90	0,80	0,60	69,82	52,36	217,41	434,81	138,41	18,97	1650	2086,94	55,19	8,03
105	0,69	0,50	60,43	43,78	233,68	467,36	148,76	17,44	1650	2366,63	50,73	9,56
120	0,62	0,40	53,71	34,88	247,88	495,76	157,81	15,87	1650	2610,77	46,18	11,13
135	0,56	0,30	49,02	26,00	259,46	518,92	165,18	14,40	1650	2809,76	41,88	12,60
150	0,53	0,20	45,94	17,23	268,00	536,01	170,62	13,15	1650	2956,63	38,25	13,85
165	0,51	0,10	44,20	8,58	273,24	546,47	173,95	12,30	1650	3046,60	35,79	14,70
180	0,50	0,00	43,64	0,00	275,00	550,00	175,07	12,00	1650	3076,90	34,91	15,00
195	0,51	-0,10	44,20	-8,58	273,24	546,47	173,95	12,30	1650	3046,60	35,79	14,70
210	0,53	-0,20	45,94	-17,23	268,00	536,01	170,62	13,15	1650	2956,63	38,25	13,85
225	0,56	-0,30	49,02	-26,00	259,46	518,92	165,18	14,40	1650	2809,76	41,88	12,60
240	0,62	-0,40	53,71	-34,88	247,88	495,76	157,81	15,87	1650	2610,77	46,18	11,13
255	0,69	-0,50	60,43	-43,78	233,68	467,36	148,76	17,44	1650	2366,63	50,73	9,56
270	0,80	-0,60	69,82	-52,36	217,41	434,81	138,41	18,97	1650	2086,94	55,19	8,03
285	0,95	-0,69	82,65	-59,88	199,81	399,63	127,21	20,39	1650	1784,55	59,32	6,61
300	1,14	-0,74	99,74	-64,78	181,90	363,79	115,80	21,63	1650	1476,55	62,93	5,37
315	1,39	-0,74	121,27	-64,31	164,96	329,92	105,02	22,64	1650	1185,49	65,87	4,36
330	1,67	-0,62	145,34	-54,50	150,68	301,37	95,93	23,39	1650	940,07	68,04	3,61
345	1,90	-0,37	166,06	-32,23	140,97	281,94	89,74	23,85	1650	773,10	69,37	3,15
360	2,00	0,00	174,55	0,00	137,50	275,00	87,54	24,00	1650	713,45	69,81	3,00

Table 1 : $VA_c = 27kV$, $IP = 550A$, $\theta_0 = \frac{\pi}{2}$, $Vr_{min} = 3kV$, $VSWR = 2$ (see Annex 10)

φ in degree	u	v	ZT		I _{armspeak} A	IP A	I _{av} A	V _{armspeak} kV	P kW	Pd kW	η %	Vr kV
			Ohm	Ohm								
			R	X								
0	1,50	0,00	130,91	0,00	183,33	366,67	116,71	24,00	2200	951,27	69,81	3,00
15	1,47	0,16	128,18	13,82	185,28	370,55	117,95	23,89	2200	984,65	69,48	3,11
30	1,38	0,29	120,79	25,17	190,85	381,71	121,50	23,55	2200	1080,55	68,50	3,45
45	1,27	0,37	110,65	32,60	199,41	398,82	126,95	23,00	2200	1227,59	66,91	4,00
60	1,14	0,41	99,74	35,99	210,03	420,07	133,71	22,27	2200	1410,23	64,78	4,73
75	1,03	0,41	89,47	36,01	221,77	443,54	141,18	21,39	2200	1611,91	62,21	5,61
90	0,92	0,38	80,56	33,57	233,71	467,41	148,78	20,40	2200	1817,09	59,33	6,60
105	0,84	0,34	73,27	29,49	245,06	490,12	156,01	19,35	2200	2012,29	56,30	7,65
120	0,77	0,28	67,57	24,38	255,19	510,38	162,46	18,33	2200	2186,38	53,32	8,67
135	0,73	0,21	63,33	18,66	263,58	527,15	167,80	17,40	2200	2330,53	50,62	9,60
150	0,69	0,14	60,43	12,59	269,83	539,67	171,78	16,66	2200	2438,11	48,45	10,34
165	0,67	0,07	58,74	6,33	273,70	547,39	174,24	16,17	2200	2504,48	47,04	10,83
180	0,67	0,00	58,18	0,00	275,00	550,00	175,07	16,00	2200	2526,90	46,54	11,00
195	0,67	-0,07	58,74	-6,33	273,70	547,39	174,24	16,17	2200	2504,48	47,04	10,83
210	0,69	-0,14	60,43	-12,59	269,83	539,67	171,78	16,66	2200	2438,11	48,45	10,34
225	0,73	-0,21	63,33	-18,66	263,58	527,15	167,80	17,40	2200	2330,53	50,62	9,60
240	0,77	-0,28	67,57	-24,38	255,19	510,38	162,46	18,33	2200	2186,38	53,32	8,67
255	0,84	-0,34	73,27	-29,49	245,06	490,12	156,01	19,35	2200	2012,29	56,30	7,65
270	0,92	-0,38	80,56	-33,57	233,71	467,41	148,78	20,40	2200	1817,09	59,33	6,60
285	1,03	-0,41	89,47	-36,01	221,77	443,54	141,18	21,39	2200	1611,91	62,21	5,61
300	1,14	-0,41	99,74	-35,99	210,03	420,07	133,71	22,27	2200	1410,23	64,78	4,73
315	1,27	-0,37	110,65	-32,60	199,41	398,82	126,95	23,00	2200	1227,59	66,91	4,00
330	1,38	-0,29	120,79	-25,17	190,85	381,71	121,50	23,55	2200	1080,55	68,50	3,45
345	1,47	-0,16	128,18	-13,82	185,28	370,55	117,95	23,89	2200	984,65	69,48	3,11
360	1,50	0,00	130,91	0,00	183,33	366,67	116,71	24,00	2200	951,27	69,81	3,00

Table 2 : $VA_c = 27kV$, $IP = 550A$, $\theta_0 = \frac{\pi}{2}$, $Vr_{min} = 3kV$, $VSWR = 1.5$

Table 1 and Table 2 show the large variation of the operating point for a VSWR of 2 and a VSWR of 1.5. Especially, the level of RF power allowable is strongly dependent of the value of the VSWR.

With an anode voltage constant at a value defined for the highest impedance, the dissipated power covers a very wide range and its maximum value passes beyond the dissipated capability of tetrodes. This is why operation ON VSWR required generally an anode power supply variable an control with the dissipated power an the screen grid current.

A specification can not required a specific anode efficiency without indicating clearly, the value of the maximum VSWR and the specific phase.

For the moment the size of the tube compared to the wave length is not taken into account and therefore the distribution of the dissipated power is uniform along the axis. We will see, in the following paragraph, that for frequencies, it is not the case.

The simplified model used is very helpfull to understand the behavior of a tetrode to the respect of a VSWR and the consequence on the different parameters.

3.5 Tetrodes Coupled by 3dB couplers

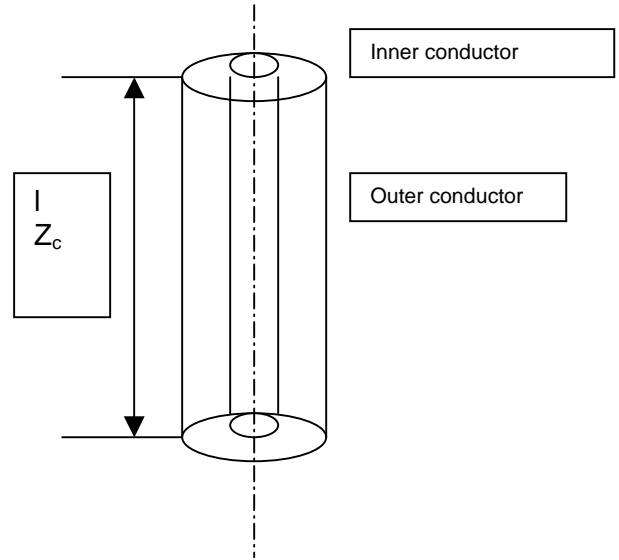
When 3 dB couplers are used to combine two amplifiers equipped with tetrode, the reflection coefficient of the real load is seen, as demonstrated in Annex 2, by the two tetrodes. Unfortunately, the phases are different and as demonstrated above, the load seen by each tetrode is different. Therefore if a single power supply is used to feed the two tetrodes it is impossible to optimize the operating point for each one. The power supply will be adjusted for the worst operating points.

4 Influence of the frequency

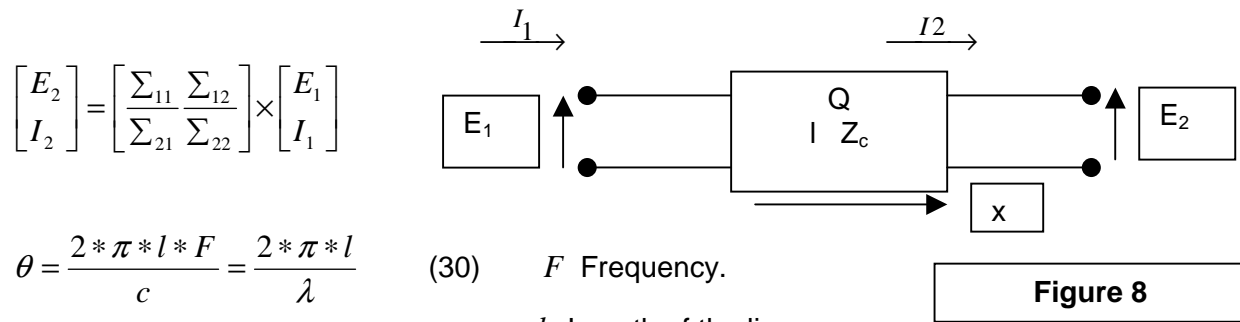
4.1 Coaxial line

Assume a coaxial line with a length l and a characteristic impedance Z_c

Figure 7



This line is a two-port circuit with a matrix described as follows:



$$\theta = \frac{2 * \pi * l * F}{c} = \frac{2 * \pi * l}{\lambda}$$

(30)

F Frequency.

l Length of the line.

c Speed of the light.

λ wave length.

Z_c Characteristic impedance

$$E_2 = \cos(\theta) * E_1 - j * \sin(\theta) * Z_c * I_1 \quad (31)$$

$$I_2 = -j * \frac{\sin(\theta)}{Z_c} * E_1 + \cos(\theta) * I_1 \quad (32)$$

$$E_2 = E_1 * (\cos(\theta) - j * \sin(\theta) * \frac{Z_c}{Z_1}) \quad (33)$$

$$I_2 = \frac{E_1}{Z_c} * (-j * \sin(\theta) + \cos(\theta) * \frac{Z_c}{Z_1}) \quad (34)$$

with Z_1 impedance load: $Z_1 = \frac{E_1}{I_1}$

Assuming Z_1 is large compared to Z_c , $\frac{Z_c}{Z_1}$ is small. Then:

$$E_2 \approx \cos(\theta) * E_1 \quad (35)$$

$$I_2 \approx -j * \sin(\theta) * \frac{E_1}{Z_c} \quad (36)$$

Everything looks like there is an open circuit at the input of the two-port circuit.

The RF losses are mainly dependent of the reactive current. We assume here that the losses are mainly on the inner conductor. The losses resistance per unit of length is inversely proportional to the skin depth.

$$\delta = \sqrt{\frac{1}{\mu * \pi * F * \sigma}} \quad \text{skin depth}$$

where $\mu = \mu_0 * \mu_r$

$\mu_0 = 4 * \pi * 10^{-7} \text{ H/m}$, permeability of vacuum,

$\mu_r = 1$, relative permeability of the conductor,

F Hz, frequency,

σ $\Omega^{-1}.m$, electrical conductivity of the conductor.

$$R_{losses} \approx \frac{k_1 * dx}{\delta}$$

The RF losses per unit of length are proportional to:

$$P_{losses}(x) \approx R_{losses} * \left(\frac{\sin(\theta(x))}{Z_c} * E_1 \right)^2 = \frac{k_1 * dx}{\delta} * \left(\frac{E_1}{Z_c} \right)^2 * \left(\sin\left(\frac{2 * \pi * F * x}{c} \right) \right)^2$$

$$P_{losses}(x) \approx k * \sqrt{F} * \left(\frac{E_1}{Z_c} \right)^2 * \left(\sin\left(\frac{2 * \pi * F * x}{c} \right) \right)^2 \quad (37)$$

$$\left(\frac{2 * \pi * F * x}{c} \right) \quad \text{electrical angle}$$

Remark

$$\text{If } \left(\frac{2 * \pi * F * x}{c} \right) \cong 0 \quad P_{losses}(x) \approx K * x^2 * F^{\frac{5}{2}}$$

We find a well known formula, which is good only if the electrical angle is close to zero.

With l length of the circuit, the RF losses in the last units of length are:

$$P_{losses}(l) \approx k * \sqrt{F} * \left(\frac{E_1}{Z_c} \right)^2 * \left(\sin \left(\frac{2 * \pi * F * l}{c} \right) \right)^2 \quad (38)$$

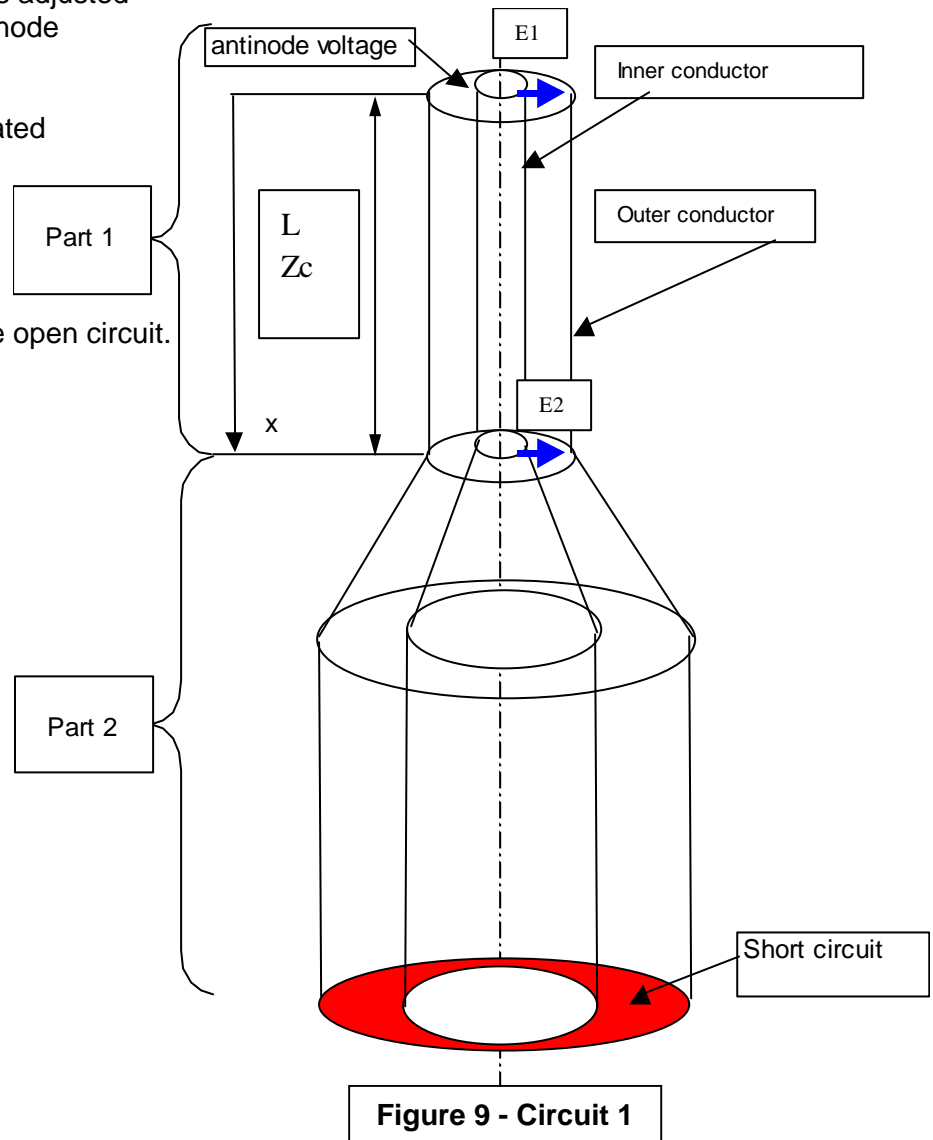
4.2 Coaxial cavity

Let us apply the previous reasoning to a coaxial circuit.

The position of the short circuit is adjusted in such a way to present an antinode voltage at the top.

The maximum voltage E_1 is located at the top.

The cavity is tune in " $\lambda/4$ ", i.e. first frequency resonance between the short circuit and the open circuit.



The RF losses per unit length at the bottom of the inner conductor of Part 1 are (eq. 37):

$$P_{losses}(l) \approx k * \sqrt{F} * \left(\frac{E_1}{Z_c} \right)^2 * \left(\sin \left(\frac{2 * \pi * F * l}{c} \right) \right)^2 \quad (38)$$

4.3 Coaxial cavity with end capacitance

The top of a cavity cannot physically be an open circuit: usually the circuit is closed with a capacitance. This capacitance increases the reactive current, so the losses.

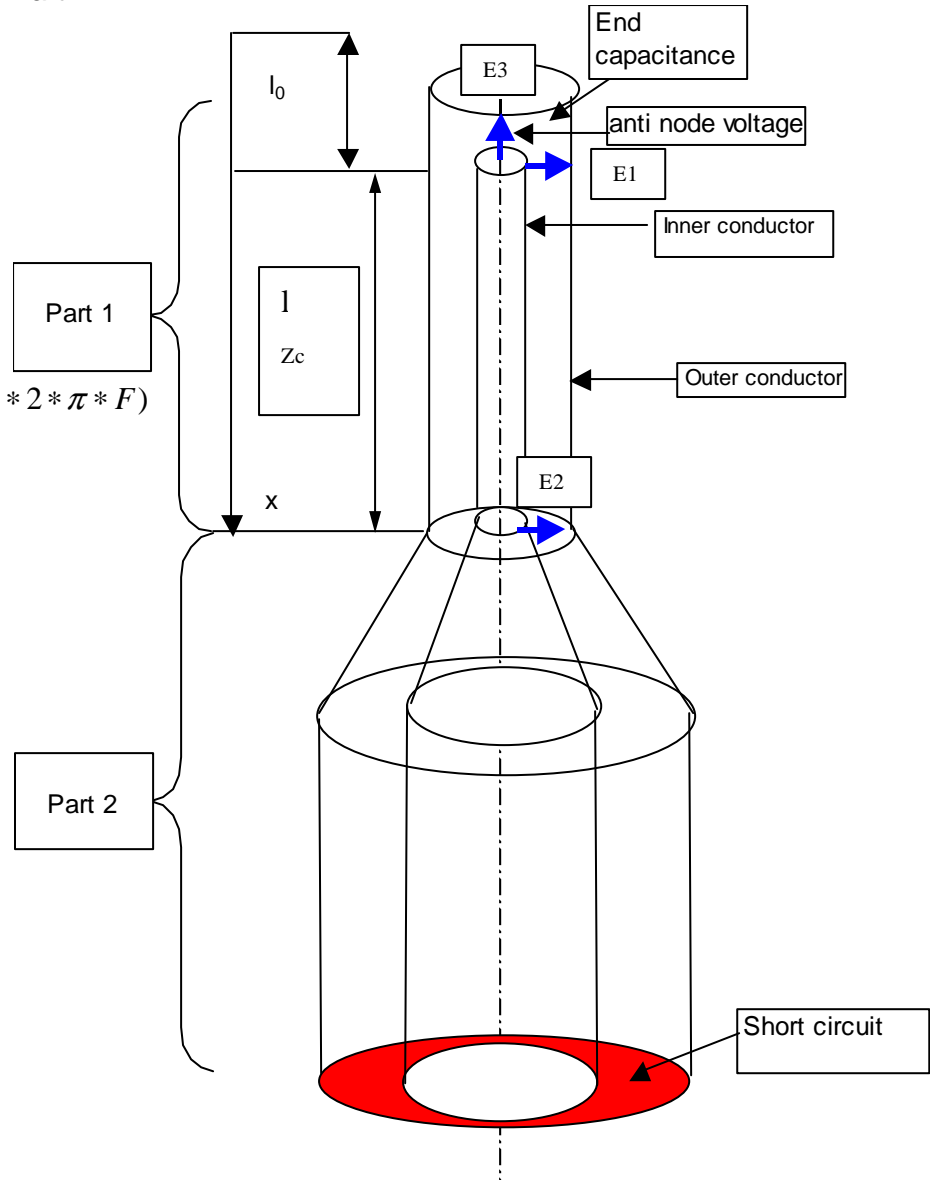
The end capacitance can be represented as a piece of line with the characteristic impedance Z_c of Part 1.

C_{end} is the end capacitance

The equivalent length of the line is then given by:

$$l_0 = \frac{c}{2 * \pi * F} * A \tan(Z_c * C_{end} * 2 * \pi * F)$$

$$E_3 = \frac{E_1}{\cos\left(\frac{2 * \pi * l_0 * F}{c}\right)}$$



$$E_2(x) = \frac{E_1}{\cos\left(\frac{2 * \pi * l_0 * F}{c}\right)} * \cos\left(\frac{2 * \pi * x * F}{c}\right) \quad (39)$$

$$I_2(x) = -J * \frac{E_1}{\cos\left(\frac{2 * \pi * l_0 * F}{c}\right)} * \sin\left(\frac{2 * \pi * x * F}{c}\right) \quad (40)$$

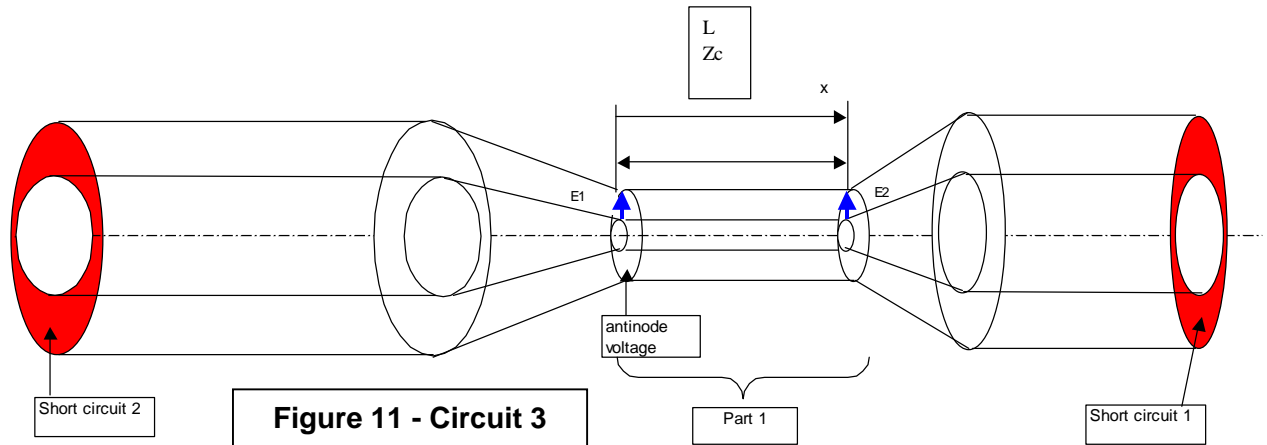
The RF losses per unit length at the bottom of the inner conductor of Part 1 are:

$$P_{losses}(l_0 + l) \approx k * \sqrt{F} * \left(\frac{E_1}{\cos\left(\frac{2 * \pi * l_0 * F}{c}\right)} \right)^2 * \left(\sin\left(\frac{2 * \pi * F * (l_0 + l)}{c}\right) \right)^2 \quad (41)$$

The end capacitance increases the drop of the voltage and the RF losses at the bottom of the inner conductor of Part 1.

4.4 Dual cavity

Let assume now that we add a new coaxial resonant circuit at the top of Circuit 1.

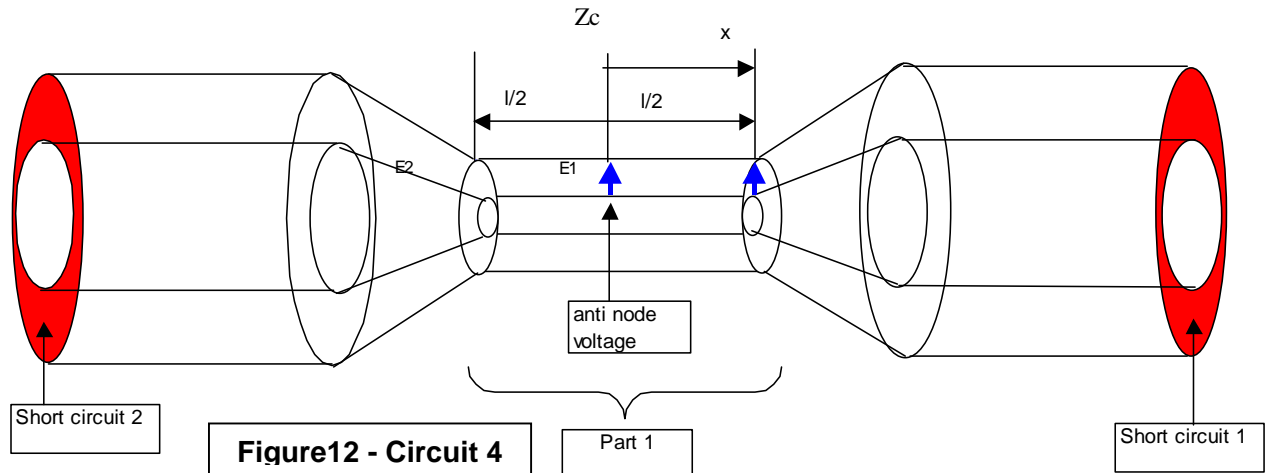


The short circuits 1 and 2 are adjusted in such a way that the antinode voltage circuit is located at the beginning of Part 1. The cavity is tune in " $\lambda/2$ ".

The RF losses per unit length at the bottom of the inner conductor of Part 1 are still given by:

$$P_{losses}(l) \approx k * \sqrt{F} * \left(\frac{E_1}{Z_c} \right)^2 * \left(\sin\left(\frac{2 * \pi * F * l}{c}\right) \right)^2 \quad (42)$$

It is possible to tune the second circuit, with short circuits1 and 2, in such a way that the antinode voltage is located in the middle of the Part 1.



For Circuit 4, the RF losses per unit length at the bottom of the inner conductor of Part 1 are still given by:

$$P_{losses}(l/2) \approx k * \sqrt{F} * \left(\frac{E_1}{Z_c} \right)^2 * \left(\sin \left(\frac{2 * \pi * F * l}{2 * c} \right) \right)^2 \quad (43)$$

Comparing Circuits 1 and 4 or Circuits 3 and 4 for the RF losses per unit length at the bottom of the inner conductor of Part 1:

$$\frac{P_{losses}(l/2)}{P_{losses}(l)} = \frac{\left(\sin \left(\frac{2 * \pi * F * l}{2 * c} \right) \right)^2}{\left(\sin \left(\frac{2 * \pi * F * l}{c} \right) \right)^2} \approx \frac{1}{4} \quad (44)$$

We will see in the next paragraph that Circuit 2 is close to a circuit built around a tetrode and circuit 4 is close to a circuit built around a Diacode.

5 Tetrodes

High power tetrodes are usually build as a set of coaxial cylinders (i.e. cathode, control grid, screen grid, anode). These cylinders define three circuits:

- the input space defined by the cathode and the control grid (C-G1),
- the space defined by the control grid and the screen grid (G1-G2),
- the output space defined by the screen grid and the anode (G2-A), the RF output power being delivered in this space.

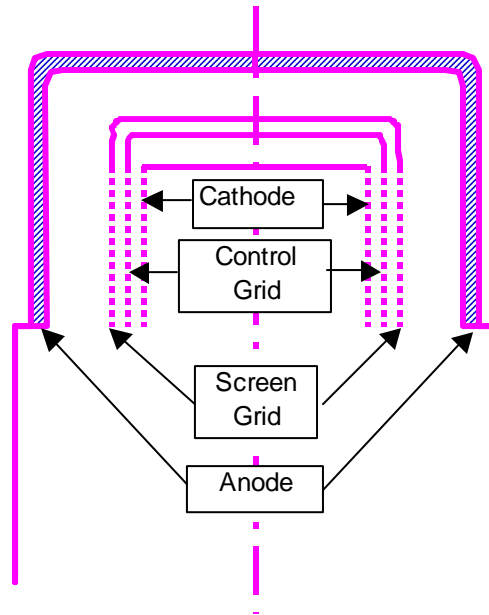


Figure 13 – Schematic of a tetrode

5.1 Losses in tetrodes

Let us focus on the G2-A space. As it was mentioned in Paragraph 1, the use of a tetrode implies necessary a resonant RF circuit.

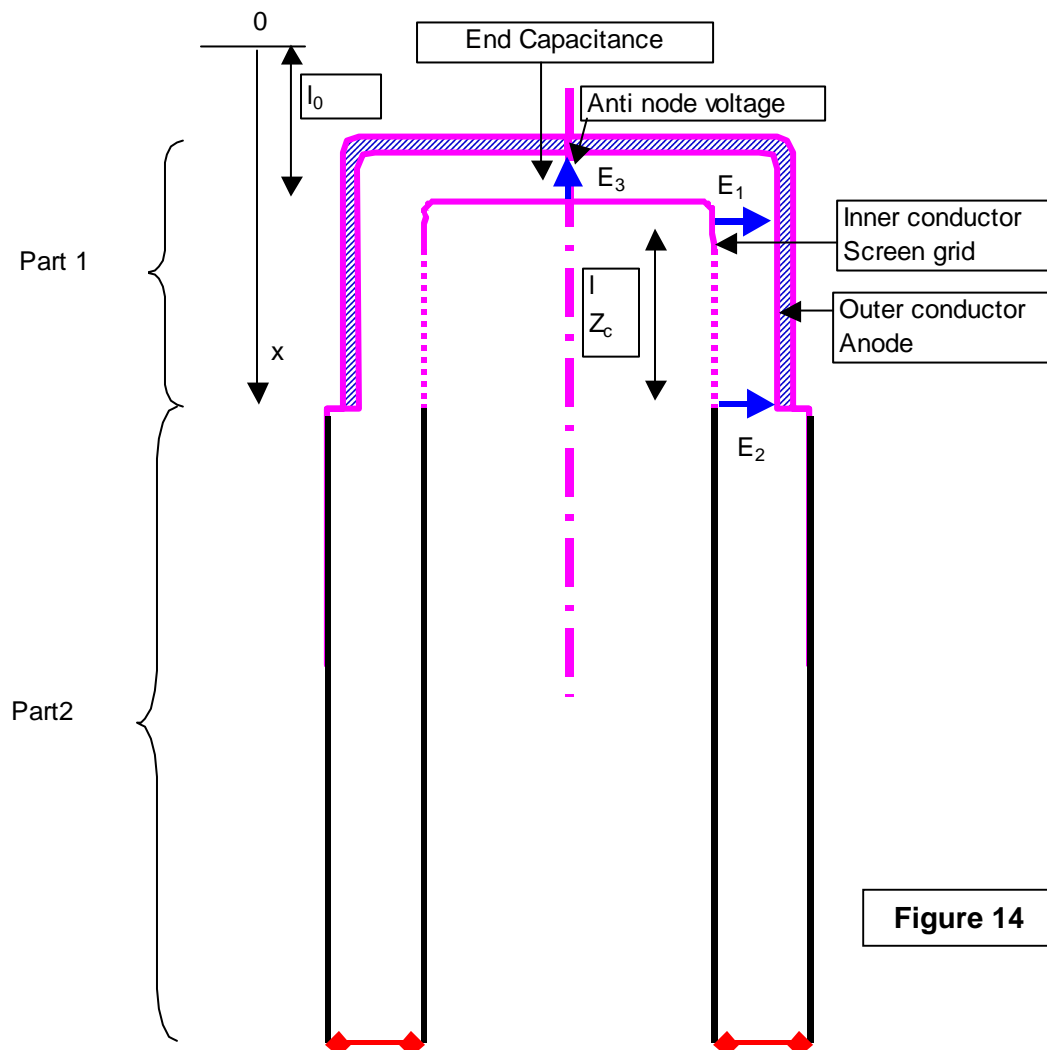


Figure 14

This circuit is exactly the same as Circuit 2: so, we can apply directly to this circuit the result achieved on Circuit 2.

$$l_0 = \frac{c}{2 * \pi * F} * A \tan(Z_c * C_{end} * 2 * \pi * F) \quad (45) \quad E_3 = \frac{E_1}{\cos\left(\frac{2 * \pi * l_0 * F}{c}\right)} \quad (46)$$

The RF losses per unit length at the bottom of the inner conductor of Part 1 are:

$$P_{losses}(l_0 + l) \approx k * \sqrt{F} * \left(\frac{E_1}{Z_c * \cos\left(\frac{2 * \pi * l_0 * F}{c}\right)} \right)^2 * \left(\sin\left(\frac{2 * \pi * F * (l_0 + l)}{c}\right) \right)^2 \quad (47)$$

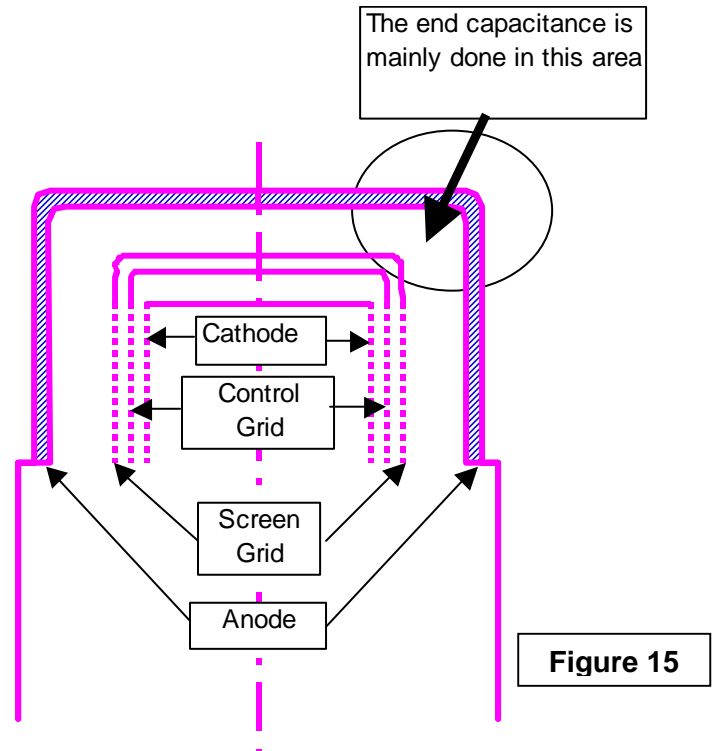
To reduce the losses at the end of the screen grid, there are two possibilities.

Either a reduction of the length of the active part and in this case, the surface of emission for the cathode is too low.

Or a reduction of the active length with a larger diameter and in this case, the end capacitance increases and the reduction of the RF losses is reduced or lost.

Note.

With a larger diameter, the frequency of the parasitic oscillation decreases and it becomes more difficult to damp this one.



5.2 Result with Thales tetrodes.

Thales tetrodes have been used for a long time in fusion application. Especially for long pulse operation such as in TORE SUPRA, JET and by General Atomic.

JET (UK) - 16 Amplifiers in operation

Tetrode	TH 525
Frequency range	25 - 60 MHz
Power	2 MW
Pulse length	10 s
Duty factor	10 %
VSWR	≤ 1.5 any phase.

General Atomic (USA) - 2 Amplifiers in operation

Tetrode	TH526
Frequency range	25 - 80 MHz and 80 - 120 MHz
Power	2 MW with a derating
Pulse length	10 s
Duty factor	10%
VSWR	≤ 1.5 any phase.
See Annex 9	

Tore supra (FR) - 6 Amplifiers in operation.

Tetrodes	TH526, TH525, TH525A
Frequency range	35 - 80 MHz and 120 MHz
Power	2 MW 1 MW
Pulse	30 s
Duty factor	12.5%
VSWR	≤ 1.5 any phase.

These performances were achieved in 1989 during the acceptance tests. Among all the tests, a seven hours test at 2 MW, with 30s pulses, with duty factor of 12.5% and at 57MHz has been performed (see Annex 6). The Tore Supra RF team performed long pulse tests on antenna and on dummy load, as shown in Annex 3, 4 and 7.

Note:

TH526 is a tetrode able to deliver 2 MW up to 80 MHz and 1 MW at 120 MHz under the TORE SUPRA specifications. Its capability of dissipation in RF operation is 1MW.

TH525 was next used: this tetrode is able to deliver 2MW up to 80MHz under the Tore Supra specifications. Its capability of dissipation in RF operation is 1.3MW.

Tetrode TH525A is identical to tetrode TH525, but has an extended capability of dissipation In RF operation of 1.9 MW.

The performance required by Tore Supra at 120 MHz is 1.4 MW on a VSWR ≤ 1.5 : TH526, which is shorter than TH525, showed some screen grid thermal emission for pulse longer than 10 seconds and the RF power was reduced to 1 MW. With TH525, this phenomena appeared at 80 MHz only for pulse longer than 25 seconds.

NIFS (Jp)

Tetrodes	TH525A
Frequency range	25 - 90 MHz and 120 MHz
Power	1.5 MW up to 57 MHz and derating for higher frequencies
Pulse	cw
VSWR	1

Thales factory tests

Tests in cw (pulse longer than 45 minutes) has been achieved at Thales factory. The means used for this test are a 6 MW continuous power supply connected to the prototype of the Tore Supra amplifier (see Annex 5 and 8). These tests were performed to define the highest RF power which can be achieved in cw with the highest reliability. The tetrode operated on a VSWR of 1, on very high impedance load (using the full capability of the cathode: see Paragraph 1): the maximum RF power achievable is 1500 kW cw.

As far as we know, these kinds of tests with long pulses or even in cw are the ones ever ran. All these tests made at Thales factory and at customer facilities demonstrate clearly that pulses shorter than 30 seconds are not to be considered as constant wave (cw) operation and that stationary state is not achieved.

They also demonstrate that the RF losses inside a tetrode are the main limitation.

5.3 Derating in power versus frequency for TH525

As mentioned above, tests in constant wave have been made in cw at 57 MHz with TH525. These tests allow the calculation of the RF voltage which induces a good reliability for the defined operating point.

$V_{armspeak57MHz}$ is defined by calculation based on real tests.

With the drawing of the tube, one can estimate the end capacitance C_{end} and then compute the equivalent length

$$l_0 = \frac{c}{2 * \pi * F} * A \tan(Z_c * C_{end} * 2 * \pi * F)$$

If we want to keep constant the RF losses at the bottom of the screen per unit length. Then:

$$\frac{P_{losses}(F)}{P_{losses}(57MHz)} = 1, \quad \text{so } Va_{rmspeak} \text{ for each frequency can be estimated from eq 35 and 38.}$$

$$Va_{rmspeak}(F) = Va_{rmspeak}(57MHz) * \frac{\cos\left(\frac{2 * \pi * l_0(57MHz) * F_{57MHz}}{c}\right)}{\cos\left(\frac{2 * \pi * l_0(F) * F}{c}\right)} * \sqrt{\frac{F_{57MHz}}{F}} * \frac{\sin\left(\frac{2 * \pi * (l_0(57MHz) + l) * F_{57MHz}}{c}\right)}{\sin\left(\frac{2 * \pi * (l_0(F) + l) * F}{c}\right)}$$

(48)

Using the analysis defined in the Paragraph 3, the derating in power for each frequency is derived easily.

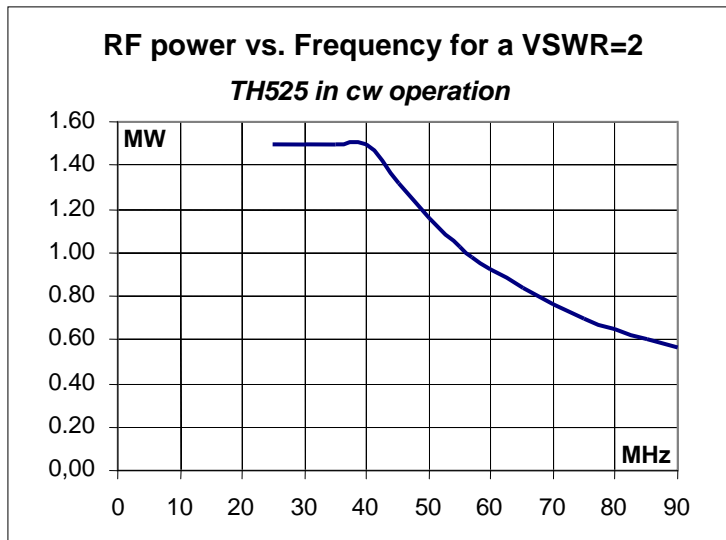


Figure 17



Figure 16 – TH525 Tetrode

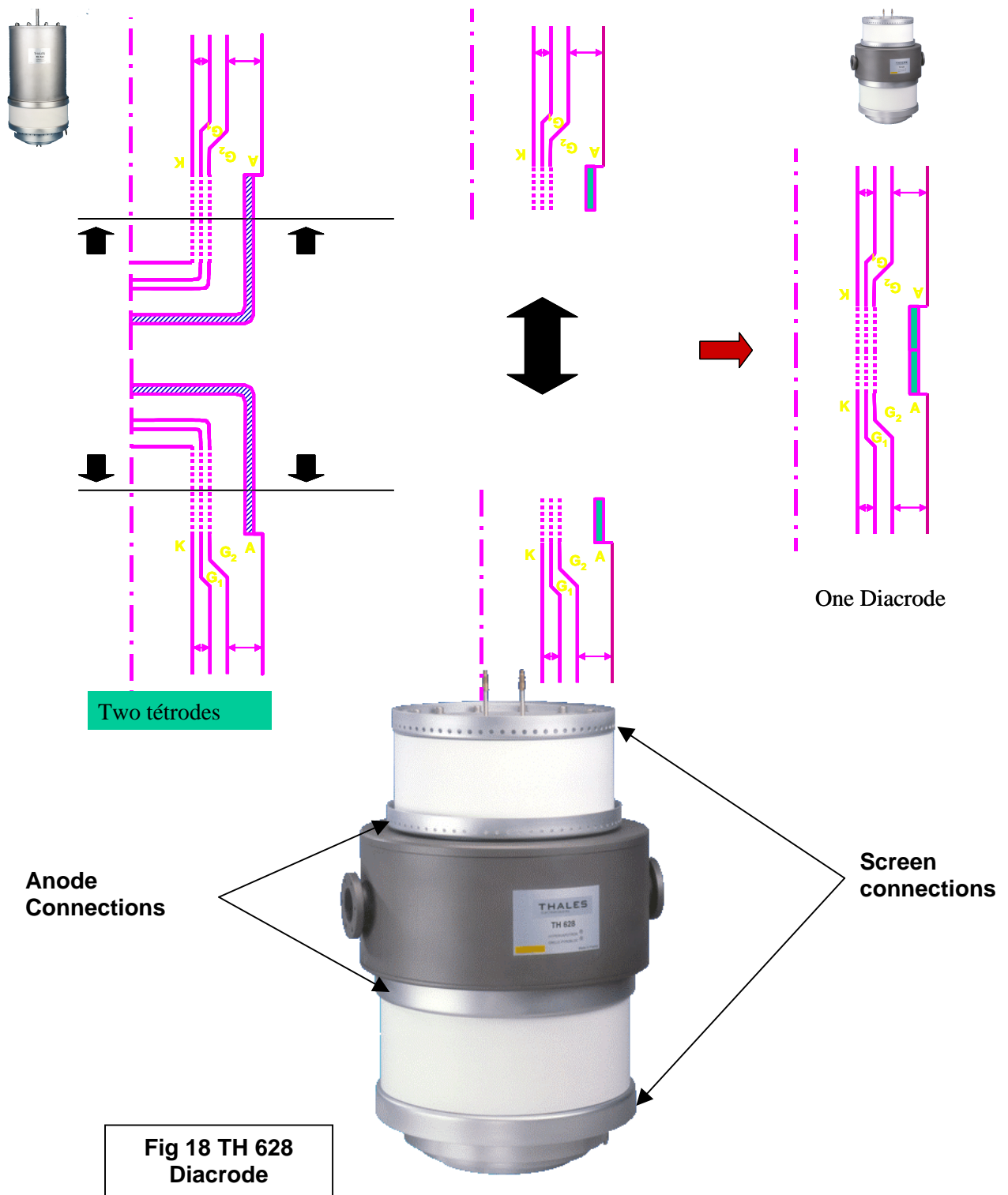
The main issue for tetrodes in constant wave operation is the RF losses. The combined effect of the VSWR and the frequency lead to strong reduction of the RF power given by the tetrode when the frequency does increase.

6 Diacode : the double-ended tetrode

Circuit 4, defined in the previous paragraph, is the circuit which presents the lowest RF losses.

The Diacode concept

The only way to replace Part 1 of a gridded tube is to make a double ended tube, two connections for the screen and for the anode, on both sides of the tube.



Form an electronic point of view a diacrode is a tetrode with double-ended connections.

The drop of the RF voltage for a Diacrode is given by

$$Va_{rmspeak}(x) = Va_{rmspeakantinode} * \cos\left(\frac{2 * \pi * l * F}{2 * c}\right)$$

The remaining voltage $Vr(x) = VA_c - Va_{rmspeak}(x)$, so the instantaneous voltage on the tube determines the current distribution all along the active part and also the distribution of the dissipated power.

For a same length of the active part and the same $Va_{rmspeakantinode}$,

For a tetrode $x_{max} = l$ and $Va_{rmspeak}(x) = Va_{rmspeakantinode} * \cos\left(\frac{2 * \pi * l * F}{c}\right)$

for a Diacrode $x_{max} = \frac{l}{2}$: and $Va_{rmspeak}(x) = Va_{rmspeakantinode} * \cos\left(\frac{2 * \pi * l * F}{2 * c}\right)$

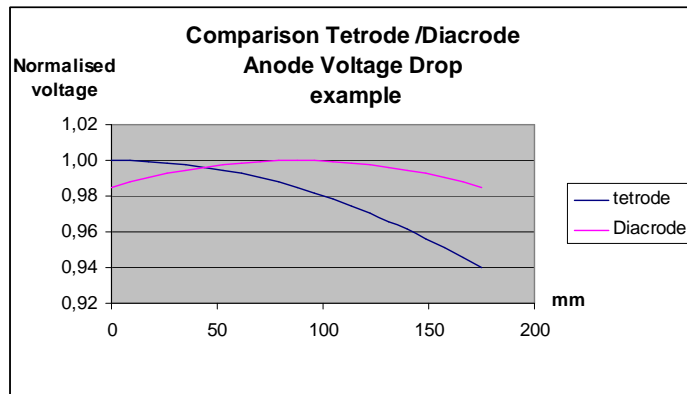


Figure 19

Therefore, it is obvious that the electronic block is better used in a Diacrode than in a tetrode, with a much better distribution, this is true when the drop voltage is significant, especially for the screen grid current.

6.1 Derating in power vs. frequency for TH 628

TH 628 has the same electronic bloc as TH 525: the length of the active part is the same.

Knowing (see previous paragraph) $Va_{rmspeak}^{TH525}$ for each frequency and keeping constant the RF losses at the bottom of the screen per unit length, then:

$$P_{losses}^{TH525} = P_{losses}(l_0(F) + l) \approx k * \sqrt{F} * \left(\frac{Va_{rmspeak}^{TH525}(F)}{Z_c * \cos\left(\frac{2 * \pi * l_0(F) * F}{c}\right)} \right)^2 * \left(\sin\left(\frac{2 * \pi * F * (l_0(F) + l)}{c}\right) \right)^2$$

(49)

$$P_{losses TH 628} = P_{losses} (l / 2) \approx k * \sqrt{F} * \left(\frac{Va_{rmspeak TH 628(F)}}{Z_c} \right)^2 * \left(\sin \left(\frac{2 * \pi * F * l}{2 * c} \right) \right)^2$$

(50)

It is then easy to estimate the values of $Va_{rmspeak TH 628}$ for each frequency.

Using the analysis defined in the Paragraph 3, the derating in power for each frequency is straightforward.

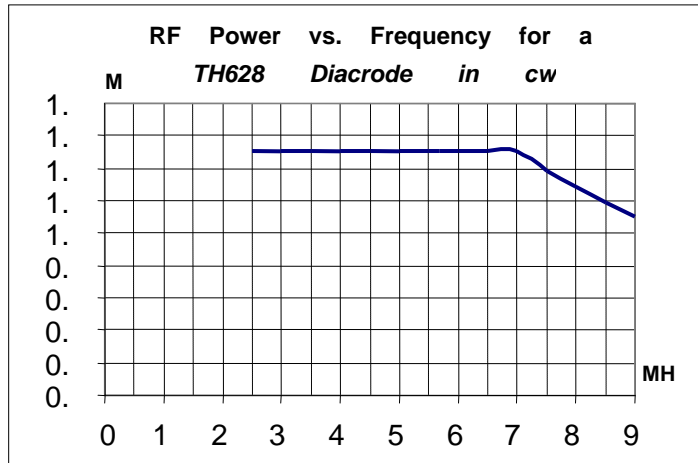


Figure 20 - Derating in power versus frequency for TH628



Figure 21 - TH628 Diacrode

The derating of the TH628 Diacrode compared to the TH525 tetrode shows clearly an improvement. This is only due to the reduction of the RF losses inside the tube by doubling the connections and tuning the electronic tube in half wavelength in such a way that the maximum RF voltage is located in the middle of the active part.

6.2 TH628 Results

TH628 is the most powerful gridded tube ever been built. At 200 MHz, this tube can deliver, on a dummy load, 1 MW in constant wave operation. Several results have been obtained.

- EFDA contract to test a TH 628 during 1000 hours on a VSWR of 1.1:1, in order to evaluate any change in performance. The tests have been successful and this particular TH 628 is still used for tests at Thales facilities (Contract :FU05 CT 2001 – 00135 (EFDA /00- 926);
- IBA (Ion Beam Applications), a company in Belgium, is using TH 628 in one of their equipment at a power of 1000 kW in cw operation, at the frequency of 107 MHz.;
- Los Alamos National Lab (LANL) has ran at Thales facilities an Acceptance Test at a power of 3 MW peak, with pulse duration of 1.2 ms, a duty factor of 20% (i.e. 600 kW average power) and no built an RF circuit to use the TH628 on its accelerator.

TH628 has never been tested in a real fusion application: nevertheless, one should remind that the electronic block (cathode, grid1, grid2 and anode) is the same that TH525 used at JET (UK) and Tore Supra (FR).

7 Conclusion

The different paragraphs of this document have shown to the designer of a RF amplifier the interesting performance of tetrodes but also, their limitations especially on VSWR and in frequency.

The best way to understand the behaviour of tetrodes is to understand the fundamental notion of tube load and its effect on the operating point.

Beside the theoretical presentations, which can be applied to any tetrode, as soon as the full set of data is available, one important point is the description of the double-ended tetrodes, known at Thales for years as the **Diacrode technology**, used for TV broadcast and industrial applications. Starting from the limitations of conventional tetrodes, the reader has been brought to this technology in order to overpass the performance of tetrodes when higher performance are required.

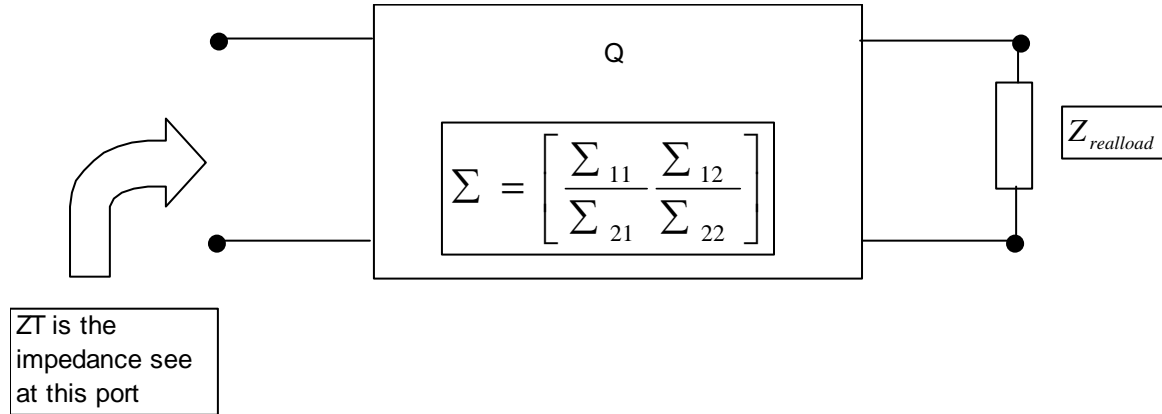
The second important point shown in this document is the different results, in operation, using high power tubes, either conventional tetrodes or Diacrodes, with long pulse durations and in **cw operation**. The values have been obtained in the Thales premises and also, on different sites all around the world, some of them for Fusion applications: the latter are also important in respect to the future Fusion installations of ITER, for which, the ICRH system will be based, for the RF amplification, on the use of tetrodes or double-ended tetrodes.

ITER will require a large RF frequency range, a high power, an operation under a high VSWR value and also, a cw operation, that is to say, more than 1000 seconds.

The present document has clearly shown that a result obtained with few second pulse duration will not prove to be effective for a 1000 second cw operation.

As far as published results are concerned, different Thales tetrodes (including double-ended tetrode technology, i.e. Diacrodes) have been successfully tested in very long pulse operation as well as, which is more important, in cw operation: these unique results give **high power Thales tetrode technology** a strong basis to meet any future requirements.

Annex 1 - VSWR at the input of a two-port device



Assuming that for $VSWR = 1$, one has:

$$Z_{realload} = R_{realload} \quad \text{and} \quad ZT = RT$$

$VSWR$ is defined by

The reflection coefficient and the $VSWR$ on the real load side are defined as:

$$\gamma_1 = \frac{Z_{realload} - R_{realload}}{Z_{realload} + R_{realload}} \quad (A_11) \quad VSWR_1 = \frac{1 + |\gamma_1|}{1 - |\gamma_1|} \quad (A_11)$$

$|\gamma_1|$ is the module of the reflection coefficient on the real load side.

The reflection coefficient on the generator side is defined as:

$$\gamma_2 = \frac{ZT - RT}{ZT + RT} \quad (A_12) \quad VSWR_2 = \frac{1 + |\gamma_2|}{1 - |\gamma_2|} \quad (A_12)$$

$|\gamma_2|$ is the module of the reflection coefficient on the generator side.

With a two ports circuit with passive components and without losses, the module of the reflection coefficient is constant.

$$|\gamma_1| = |\gamma_2| = |\gamma|$$

$$ZT = \frac{\Sigma_{11} * Z_{realload} + \Sigma_{12}}{\Sigma_{21} * Z_{realload} + \Sigma_{22}}$$

$$ZT = R + j * X$$

For a $VSWR = 1$, the following is derived:

$$RT = R = \text{Re}al\left(\frac{\sum_{11} * R_{reaload} + \sum_{12}}{\sum_{21} * R_{reaload} + \sum_{22}}\right) \quad (A_13)$$

$$X = 0 = \text{Im}ag\left(\frac{\sum_{11} * R_{reaload} + \sum_{12}}{\sum_{21} * R_{reaload} + \sum_{22}}\right) \quad (A_14)$$

The two-port circuit is made of passive components, balanced and without losses. Then:

$$\sum_{11} * \sum_{22} - \sum_{21} * \sum_{12} = 1 \quad (A_15)$$

$$\sum_{11} = a, \quad \sum_{12} = j * b, \quad \sum_{21} = j * c, \quad \sum_{22} = a$$

From A₁₅:

$$a * a - j^2 * b * c = a^2 + b * c = 1 \quad (A_16)$$

From A₁₃:

$$RT = R_{reaload} * \frac{a^2 + b * c}{a^2 + (c * R_{reaload})^2} = R_{reaload} * \frac{1}{a^2 + (c * R_{reaload})^2} \quad (A_17)$$

$$X = 0 = \frac{b * a - a * c * R_{reaload}^2}{a^2 + (c * R_{reaload})^2} \Leftrightarrow 0 = a * (b - c * R_{reaload}^2) \quad (A_18)$$

$$\gamma_2 = \frac{ZT - RT}{ZT + RT} = \frac{\frac{\sum_{11} * Z_{reaload} + \sum_{12}}{\sum_{21} * Z_{reaload} + \sum_{22}} - \frac{\sum_{11} * R_{reaload} + \sum_{12}}{\sum_{21} * R_{reaload} + \sum_{22}}}{\frac{\sum_{11} * Z_{reaload} + \sum_{12}}{\sum_{21} * Z_{reaload} + \sum_{22}} + \frac{\sum_{11} * R_{reaload} + \sum_{12}}{\sum_{21} * R_{reaload} + \sum_{22}}}$$

$$\gamma_2 = \frac{(Z_{reaload} - R_{reaload}) * (\sum_{11} * \sum_{22} - \sum_{12} * \sum_{21})}{2 * \sum_{11} * \sum_{21} * Z_{reaload} * R_{reaload} + (Z_{reaload} + R_{reaload}) * (\sum_{11} * \sum_{22} + \sum_{12} * \sum_{21}) + 2 * \sum_{12} * \sum_{22}}$$

$$\gamma_2 = \frac{(Z_{reaload} - R_{reaload}) * (a^2 + b * c)}{2 * j * a * c * Z_{reaload} * R_{reaload} + (Z_{reaload} + R_{reaload}) * (a^2 - b * c) + 2 * j * a * b}$$

From A₁₆ $a * a - j^2 * b * c = a^2 + b * c = 1$

$$\gamma_2 = \frac{(Z_{realload} - R_{realload})}{2 * j * a * c * Z_{realload} * R_{realload} + (Z_{realload} + R_{realload}) * (a^2 - b * c) + 2 * j * a * b} \quad (A_19)$$

$$\text{From (A}_18) \quad 0 = a * (b - c * R_{realload}^2) \quad a = 0 \text{ or } b = c * R_{realload}^2$$

$$1. \quad a = 0 \quad \text{and} \quad A_11 \quad \gamma_1 = \frac{Z_{realload} - R_{realload}}{Z_{realload} + R_{realload}}, \quad A_19$$

$$\gamma_2 = \frac{(Z_{realload} - R_{realload})}{(Z_{realload} + R_{realload})} * \frac{-1}{(b * c)} = \gamma_1 * \frac{-1}{(b * c)}$$

$$\text{With } A_16 \quad a * a - j^2 * b * c = a^2 + b * c = 1$$

$$b * c = 1$$

Then

$$\gamma_2 = -\gamma_1 \quad \text{therefore} \quad |\gamma_2| = |\gamma_1| \quad A_110$$

$$2. \quad b = c * R_{realload}^2 \quad \text{and} \quad A_19$$

$$\gamma_2 = \frac{(Z_{realload} - R_{realload})}{(Z_{realload} + R_{realload}) * (a^2 - b * c) + 2 * j * (a * b + a * c * Z_{realload} * R_{realload})}$$

$$\gamma_2 = \frac{(Z_{realload} - R_{realload})}{(Z_{realload} + R_{realload}) * (a^2 - c^2 * R_{realload}^2) + 2 * j * (a * c * R_{realload}^2 + a * c * Z_{realload} * R_{realload})}$$

$$\gamma_2 = \frac{(Z_{realload} - R_{realload})}{(Z_{realload} + R_{realload}) * (a^2 - c^2 * R_{realload}^2) + 2 * j * a * c * R_{realload} (R_{realload} + Z_{realload})}$$

$$\gamma_2 = \frac{(Z_{realload} - R_{realload})}{(Z_{realload} + R_{realload})} * \frac{1}{(a^2 - c^2 * R_{realload}^2) + 2 * j * a * c * R_{realload}}$$

$$\text{With } A_11 \quad \gamma_1 = \frac{Z_{realload} - R_{realload}}{Z_{realload} + R_{realload}}$$

$$\gamma_2 = \gamma_1 * \frac{1}{(a^2 - c^2 * R_{realload}^2) + 2 * j * a * c * R_{realload}} = \gamma_1 * \alpha$$

$$|\gamma_2| = |\gamma_1| * |\alpha|$$

$$|\alpha|^2 = \frac{1}{(a^2 - b * c)^2 + 4 * a^2 * c^2 * R_{realload}^2} = \frac{1}{(a^2 - c^2 * R_{realload}^2)^2 + 4 * a^2 * c^2 * R_{realload}^2}$$

$$|\alpha|^2 = \frac{1}{(a^2 + c^2 * R_{realload}^2)^2}$$

Then using $b = c * R_{realload}^2$ and A₁₆ $a^2 + b * c = 1$

$$a^2 + c^2 * R_{realload}^2 = a * a + b * c = 1$$

Then

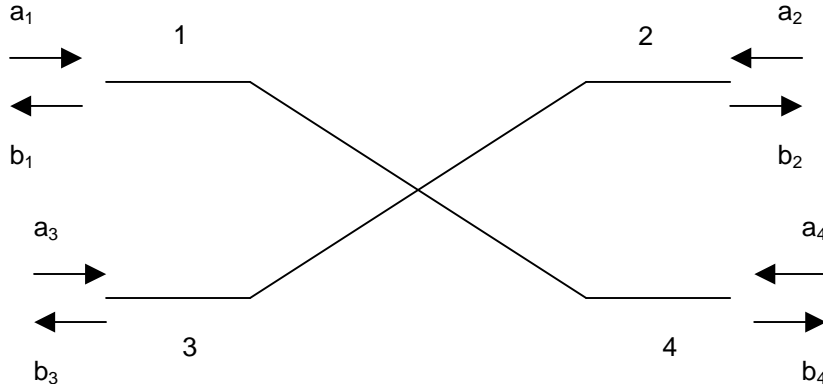
$$|\alpha|^2 = 1 \quad \Leftrightarrow \quad |\gamma_2| = |\gamma_1| \quad A_{10}$$

From A₁₁ $VSWR_1 = \frac{1+|\gamma_1|}{1-|\gamma_1|}$ and A₁₂ $VSWR_2 = \frac{1+|\gamma_2|}{1-|\gamma_2|}$ comes the conclusion that the

The $VSWR$ on the real load side and the generator side are the same, only the phase could be different.

Annex 2 - Tetrodes coupled by a 3dB coupler

Assume a 3dB coupler.



The scattering matrix is defined by:

$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} \dots 0 & \dots 1 & \dots 0 & \dots -j \\ \dots 1 & \dots 0 & \dots -j & \dots 0 \\ \dots 0 & \dots -j & \dots 0 & \dots 1 \\ -j & \dots 0 & \dots 1 & \dots 0 \end{bmatrix} \quad \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = [S]^* \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

$$\begin{aligned} b_1 &= \frac{1}{\sqrt{2}} * a_2 - \frac{j}{\sqrt{2}} * a_4 \\ b_2 &= \frac{1}{\sqrt{2}} * a_1 - \frac{j}{\sqrt{2}} * a_3 \\ b_3 &= -\frac{j}{\sqrt{2}} * a_2 + \frac{1}{\sqrt{2}} * a_4 \\ b_4 &= -\frac{j}{\sqrt{2}} * a_1 + \frac{1}{\sqrt{2}} * a_3 \end{aligned} \quad (A_21)$$

Assuming that Port 4 is completely matched and the forward wave at Port 3 has the same amplitude that the forward wave at Port 1 with a 90 degree phase.

Then:

$$a_4 = 0$$

$$\text{and} \quad (A_22)$$

$$a_3 = j * a_1 = a_1 * e^{j\frac{\pi}{2}}$$

From equations (A₂1)

$$\begin{aligned}
 b_1 &= \frac{1}{\sqrt{2}} * a_2 \\
 b_2 &= \frac{1}{\sqrt{2}} * a_1 - \frac{j^2}{\sqrt{2}} * a_1 = \frac{2}{\sqrt{2}} * a_1 = \sqrt{2} * a_1 \\
 b_3 &= -\frac{j}{\sqrt{2}} * a_2 \\
 b_4 &= -\frac{j}{\sqrt{2}} * a_1 + \frac{j}{\sqrt{2}} * a_1 = 0
 \end{aligned}
 \tag{A₂3}$$

The sum of the waves is at Port 2 and the difference of the waves is at Port 3.

Assuming that the reflection coefficient of the load at Port 2 is γ_2 .

$$\gamma_2 \text{ is defined by } \gamma_2 = \frac{a_2}{b_2} = \frac{\text{Reverse.wave.from.the.load}}{\text{Forward.wave.to.the.load}}$$

$$a_2 = \gamma_2 * b_2 \tag{A₂4}$$

The reflection coefficient from port 1 and 3 are defined by:

$$\begin{aligned}
 \gamma_1 &= \frac{b_1}{a_1} = \frac{\text{Reverse.wave.from.port1}}{\text{Forward.wave.to.port1}} \\
 \gamma_3 &= \frac{b_3}{a_3} = \frac{\text{Reverse.wave.from.port3}}{\text{Forward.wave.to.port3}}
 \end{aligned}
 \tag{A₂5}$$

From equations (A₂3) and (A₂4) : $a_2 = \gamma_2 * b_2$, $b_2 = \sqrt{2} * a_1$, $a_3 = j * a_1$

$$b_1 = \frac{1}{\sqrt{2}} * a_2 = \frac{1}{\sqrt{2}} * \gamma_2 * b_2 = \frac{1}{\sqrt{2}} * \gamma_2 * \sqrt{2} * a_1 = \gamma_2 * a_1$$

$$\gamma_1 = \frac{b_1}{a_1} = \gamma_2$$

$$b_3 = \frac{-j}{\sqrt{2}} * a_2 = \frac{-j}{\sqrt{2}} * \gamma_2 * b_2 = \frac{-j}{\sqrt{2}} * \gamma_2 * \sqrt{2} * a_1 = -j * \gamma_2 * a_1$$

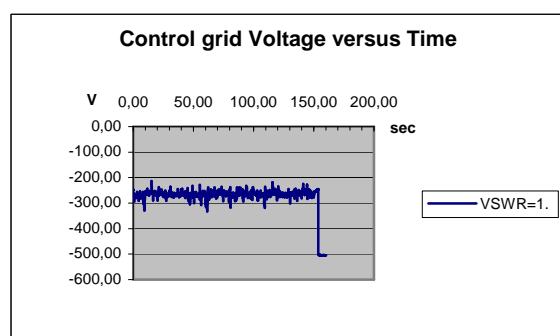
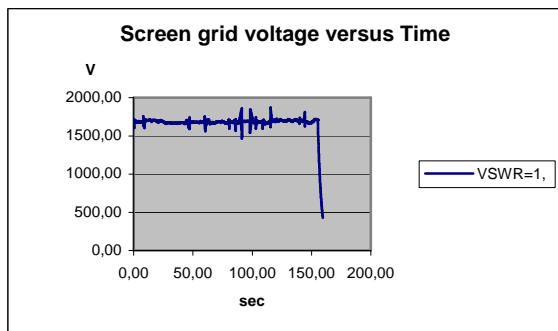
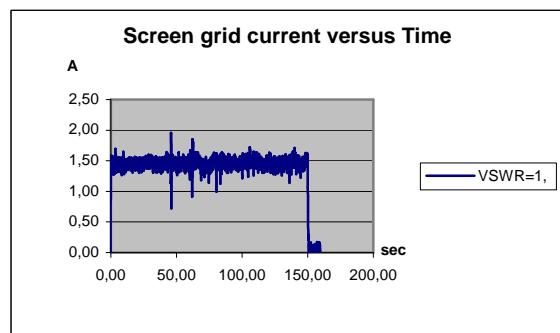
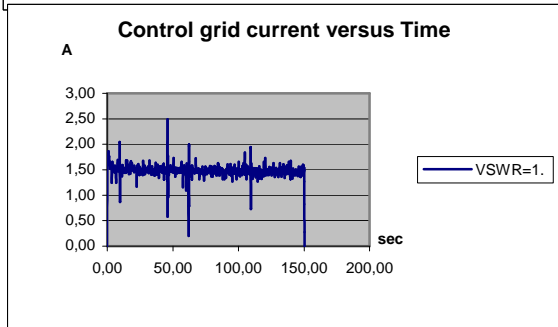
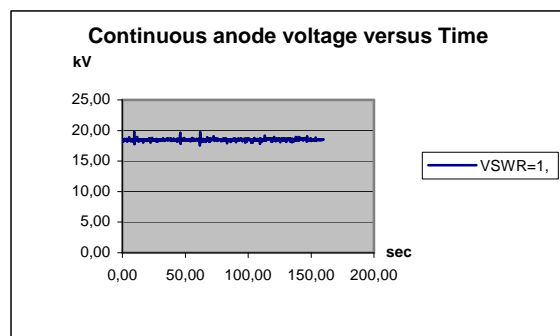
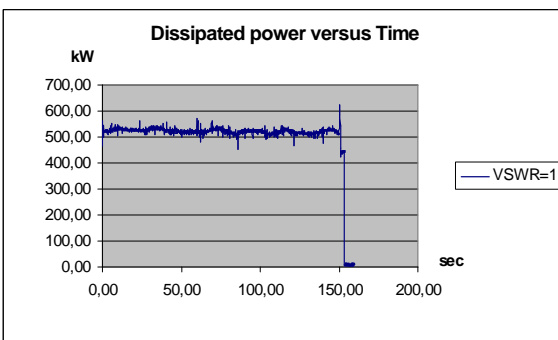
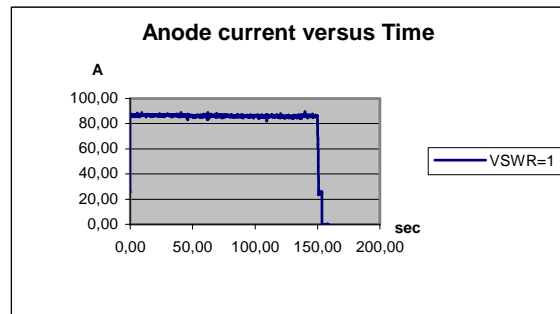
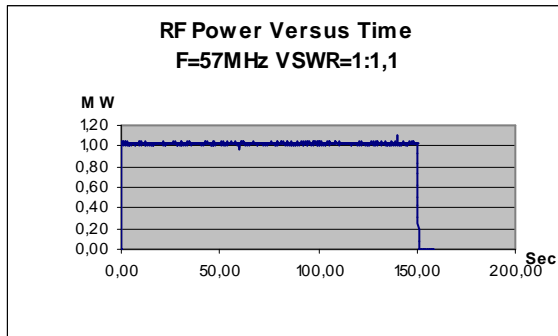
$$\gamma_3 = \frac{-j * \gamma_2 * a_1}{j * a_1} = -\gamma_2$$

Therefore the VSWR of the load is transferred to Port 1 and Port 2. If Port 1 and Port 2 are fed by tetrodes, the operating points of these one will be largely dependent on the reflection coefficient.

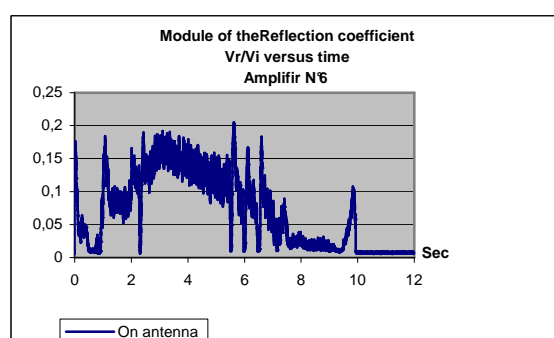
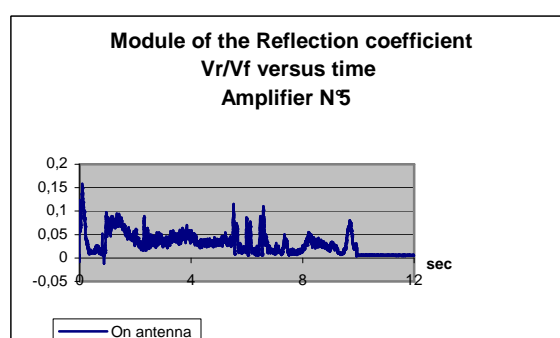
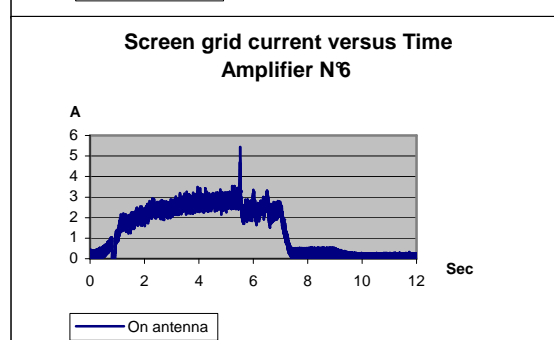
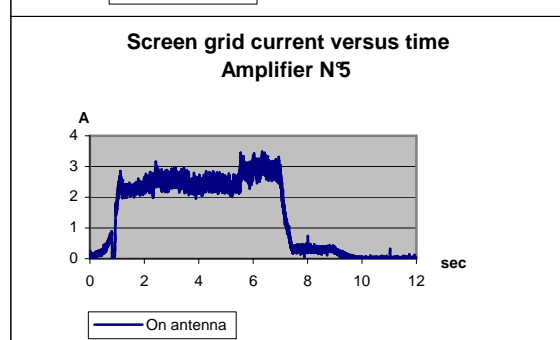
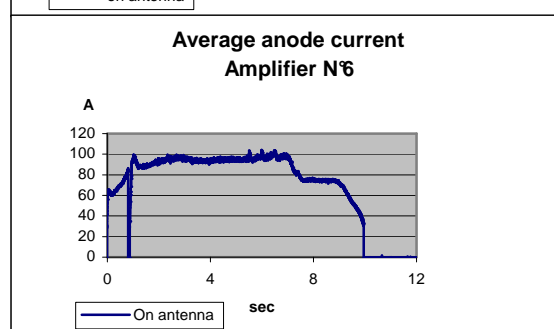
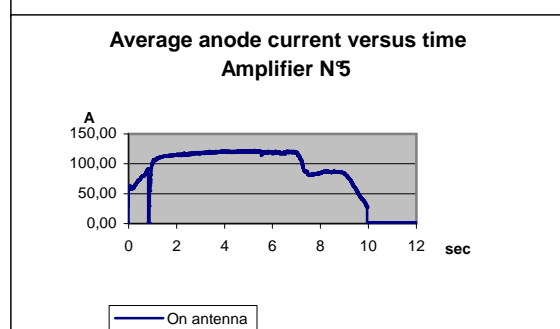
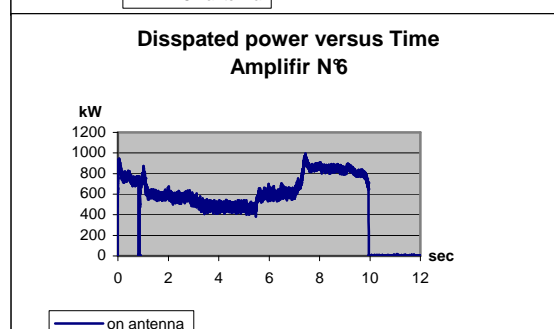
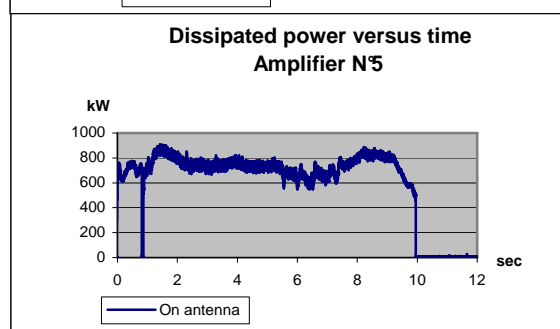
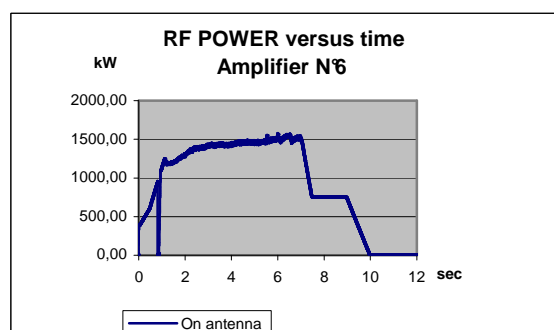
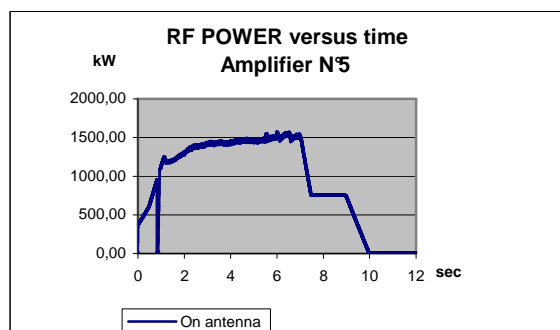
The phase of the reflection coefficient at port 1 and port 2 are different, so the operating point of each tetrode will be different and the use of a single power supply for the two tetrodes could bring some difficulties.

Annex 3 - TORE SUPRA Results.

150 second Long Pulse on dummy load with the ICRH amplifier.



Annex 4 - TORE SUPRA results on Antenna – F = 57 MHz, pulse duration = 10 s – RF Power = 1500 kW.



Annex 5 - Thales Test Bench

Cavity TH18525**For
TH526 / TH526A****TH526 / TH526A**

Frequency 35-80 MHz
Bandwidth (-1 dB) 4 MHz
Power 2000 kW
Pulse 30 s
Duty 12.5 %
VSWR ≤ 1.5 any phase
Frequency 57 MHz
Power 1500 kw cw
VSWR ≤ 1.1

Cavity TH18525**For
TH525 / TH525A****TH525 / TH525A**

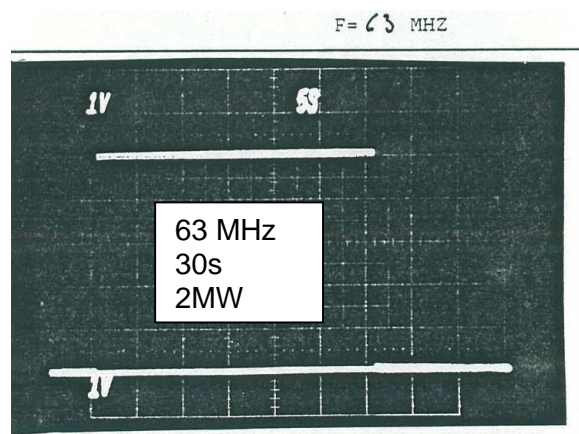
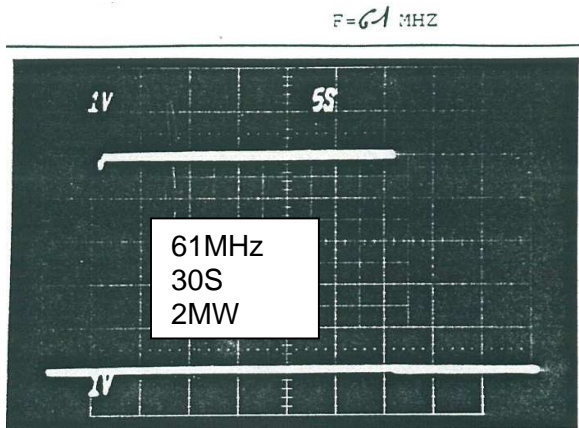
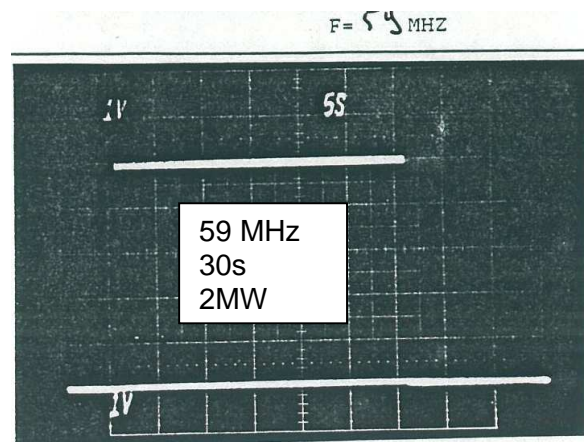
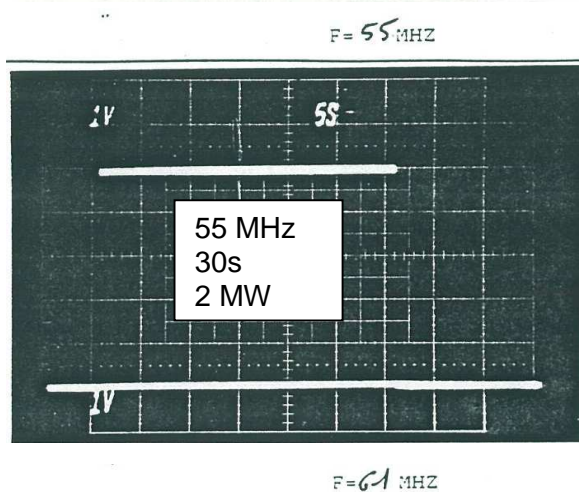
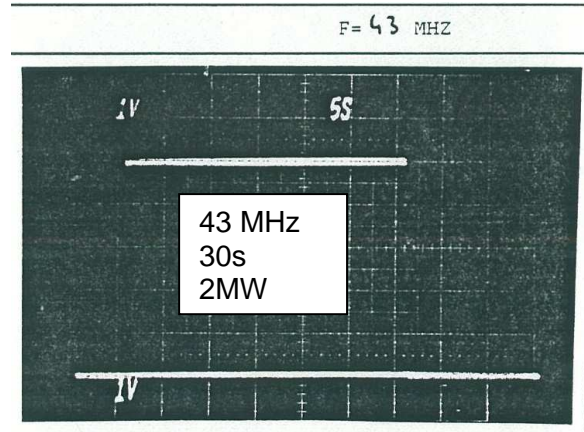
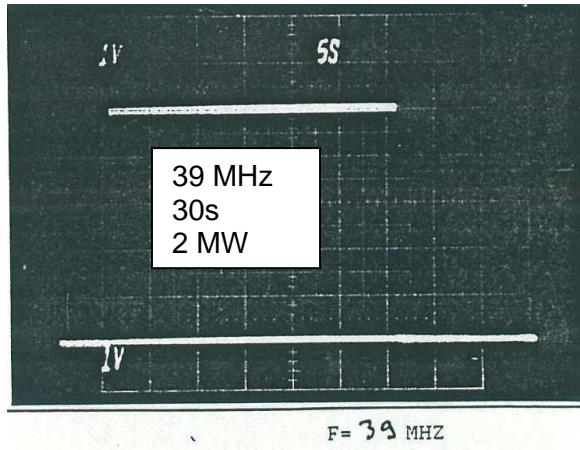
Frequency 35-70 MHz
Bandwidth (-1 dB) 4 MHz
Power 2000 kW
Pulse 30 s
Duty 12.5 %
VSWR ≤ 1.5 any phase
Frequency 57 MHz
Power 1500 kw cw
VSWR ≤ 1.1

**Dummy Load**

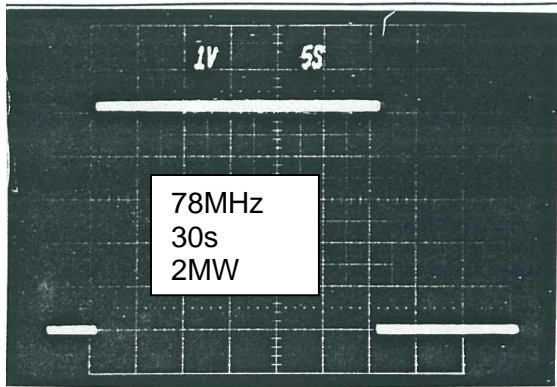
Annex 6 - TORE SUPRA - Tetrode TH526 acceptance tests

(February 21 1990)

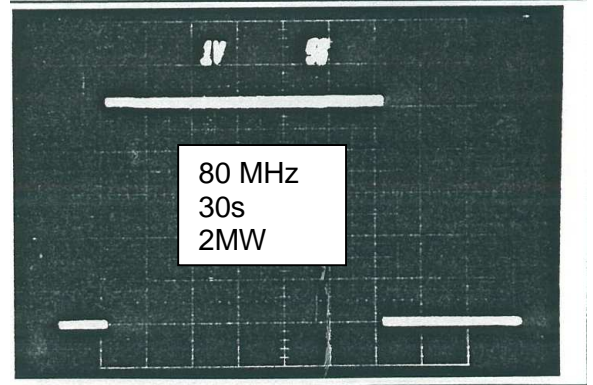
Shot 30 sec 2 MW For different frequencies:



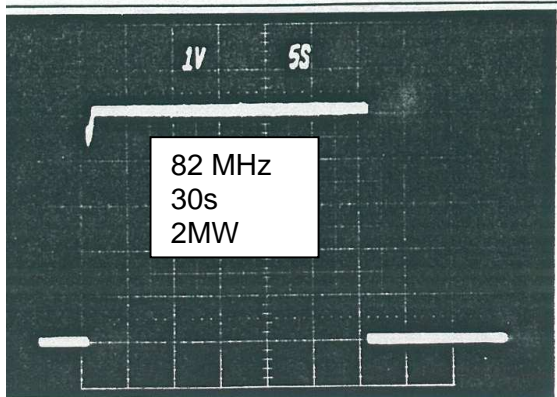
F = 78 MHz



F = 80 MHz



F = 82 MHz



Annex 7 – TORE SUPRA RF installations



A VIEW OF A TORESUPRA ICRF AMPLIFIER

LEFT	CENTER	RIGHT
5 kW stage (TH 561)	100 kW stage (TH 535)	2 MW stage (TH 526)



**Tore Supra
Command / Control
6 Amplifiers**



**Tore Supra
HPA**

Annex 8 - Thales High Power Supply

Power : 6 MW continuously
Maximum current : 200 A
Maximum voltage : 30 kV



4 transformers



Thyristors



Crow-bar



Coil



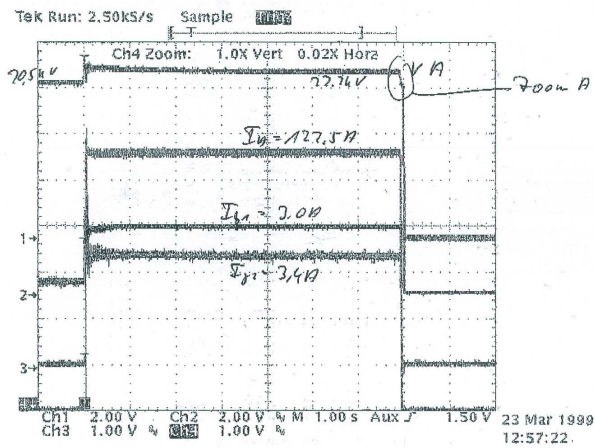
Capacitor Bank
150 μ F



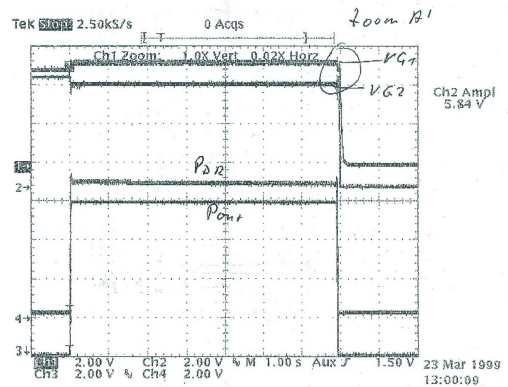
Diodes

Annex 9 - General Atomic Tests

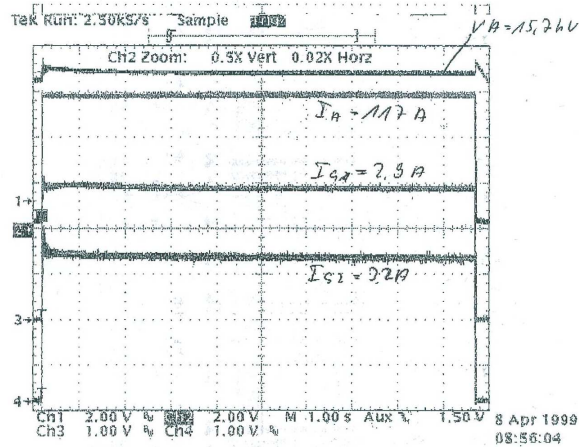
Long shot on dummy load.



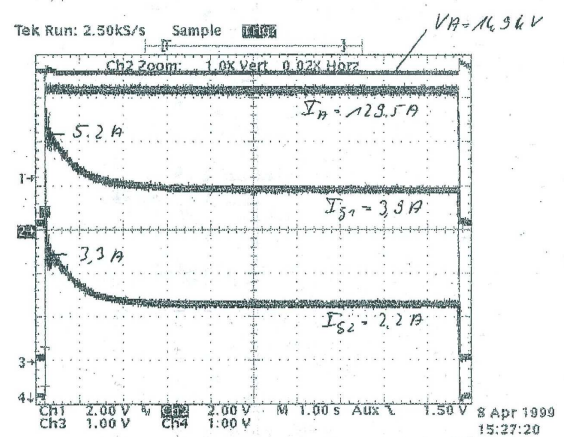
Frequency 40.7 MHz
Power 1950 kW
Pulse 9.5s



Frequency 60.3 MHz
Power 1950 kW
Pulse 9.5s



Frequency 114.9 MHz
Power 1130 kW
Pulse 9.5s



Frequency 117.6 MHz
Power 1060 kW
Pulse 9.5s

Annex 10 - Curves from Table 1 - Effect of the VSWR any phase on the operating point

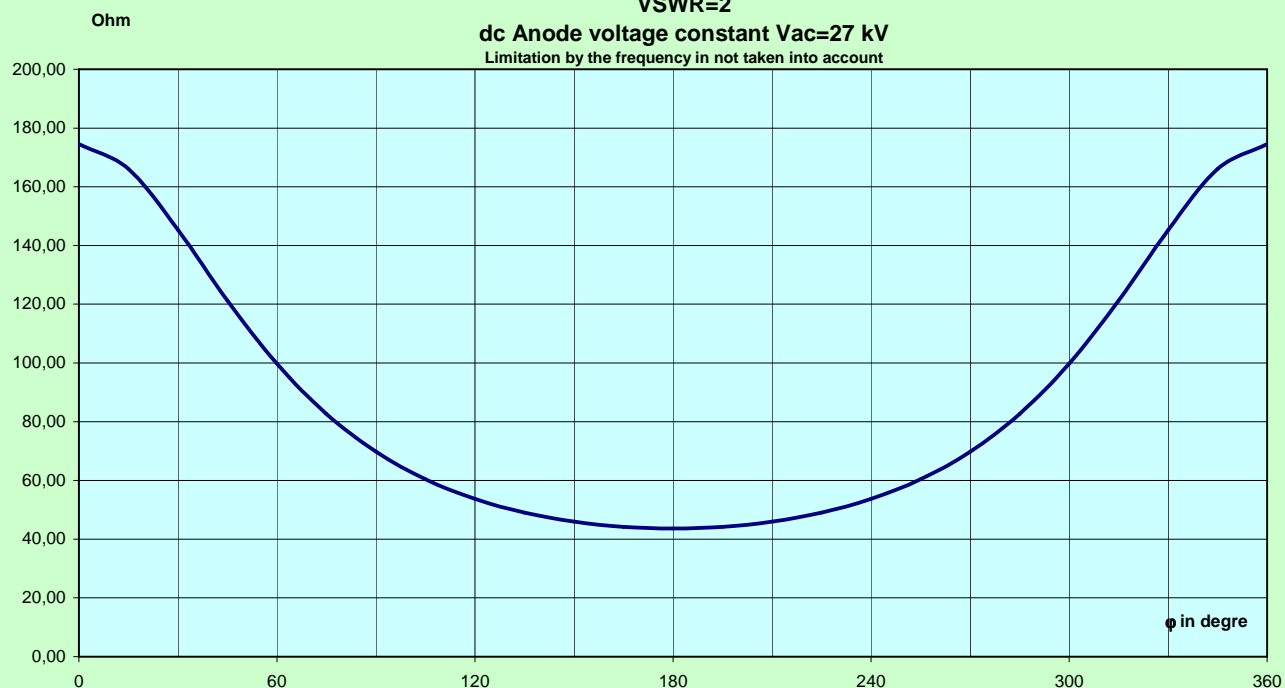
Thales tetrode TH525

Real of Load tube $R = \text{Real}(ZT)$ versus phase of reflection coefficient

VSWR=2

dc Anode voltage constant $V_{ac}=27\text{ kV}$

Limitation by the frequency is not taken into account



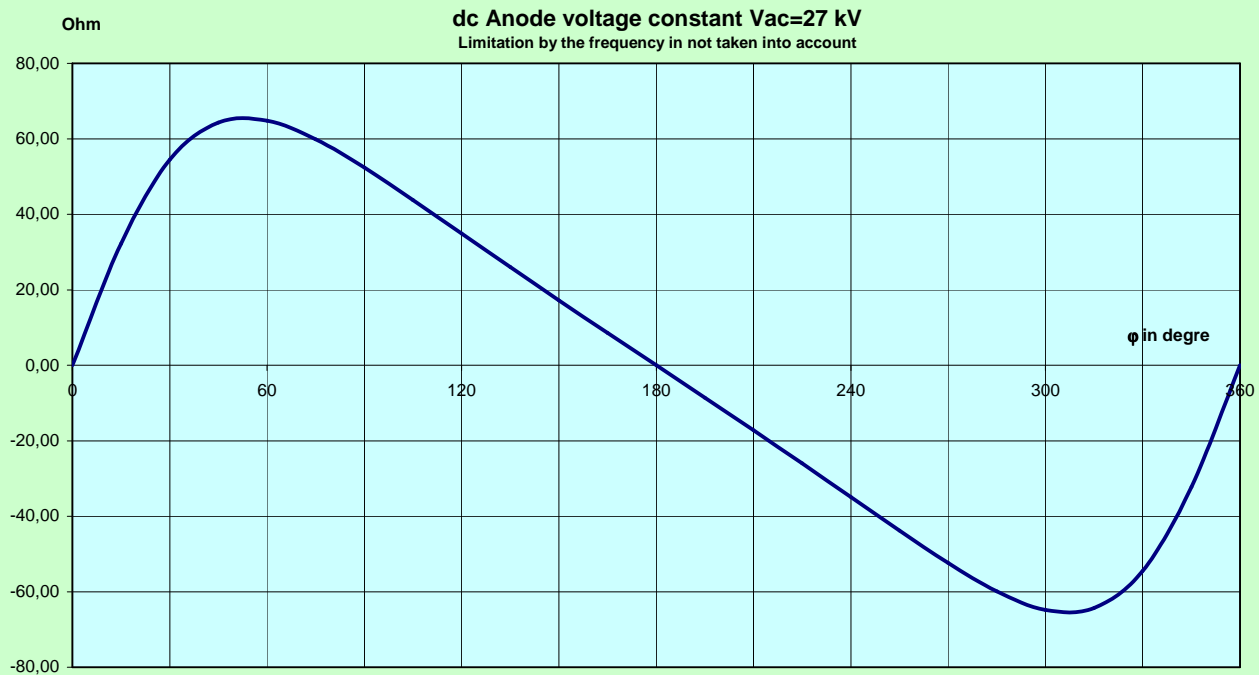
Thales tetrode TH525

Imaginary part of the tube load $X = \text{IM}(ZT)$ versus Phase of reflection coefficient

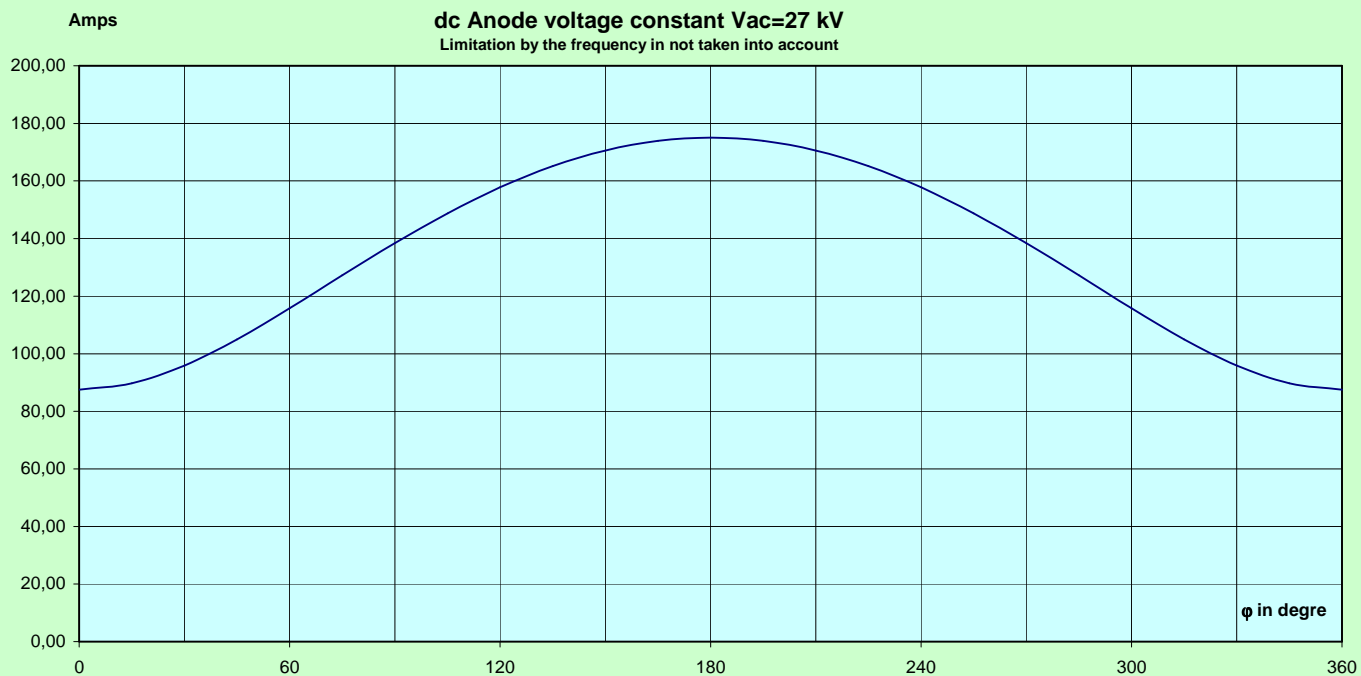
VSWR=2

dc Anode voltage constant $V_{ac}=27\text{ kV}$

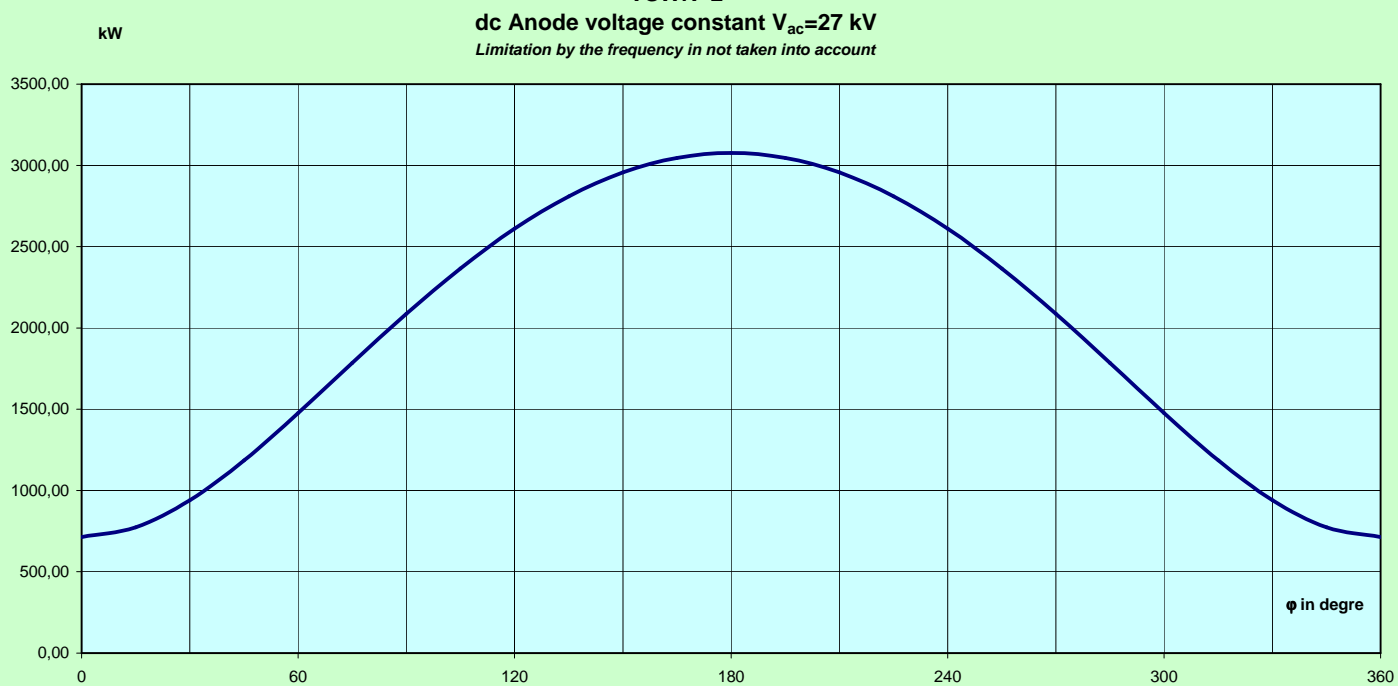
Limitation by the frequency is not taken into account



Thales tetrode TH 525 Anode
Average Current I_{av} versus Phase of reflection coefficient
VSWR=2



Thales tetrode TH525
Dissipated power versus phase of reflection coefficient
VSWR=2

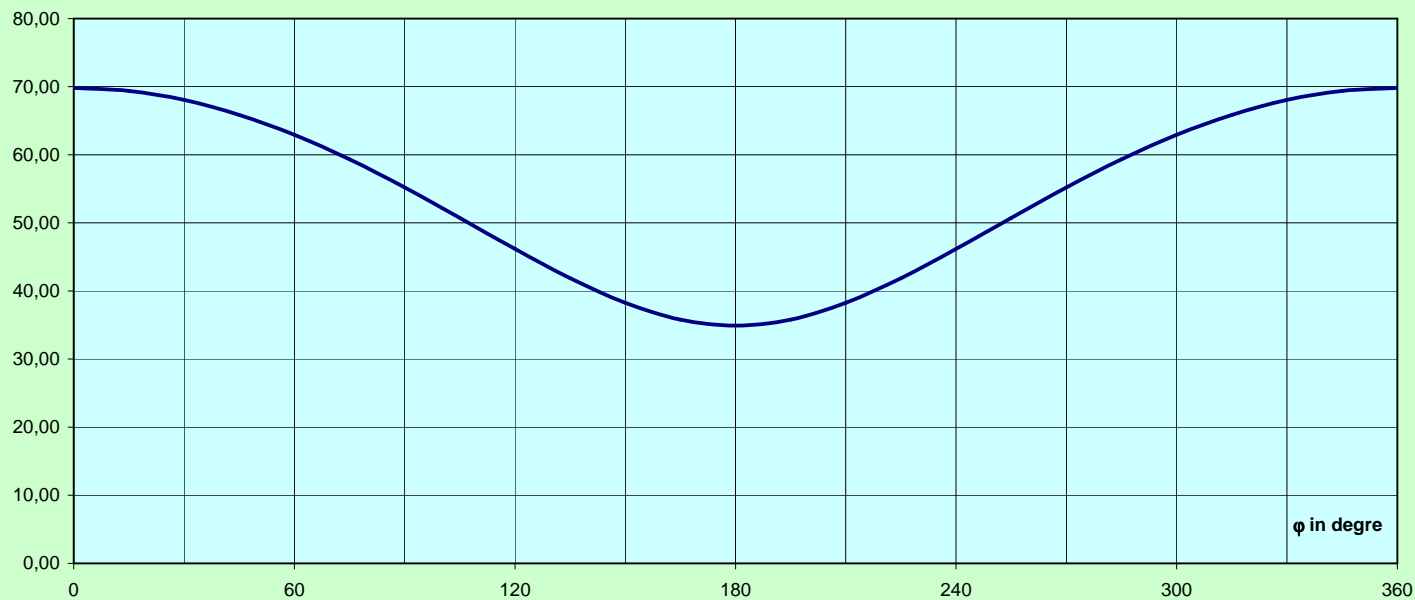


Thales tetrode TH525
Anode efficiency versus phase of reflection coefficient
VSWR=2

%

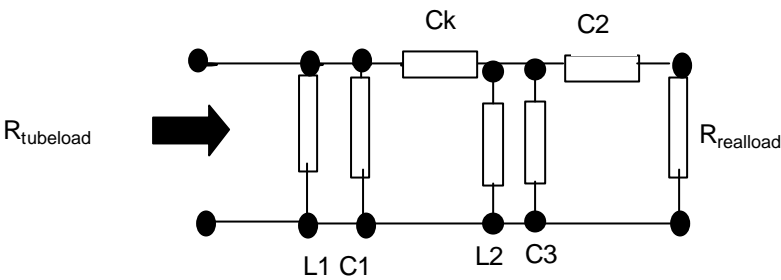
dc Anode voltage constant $V_{ac}=27$ kV

Limitation by the frequency is not taken into account

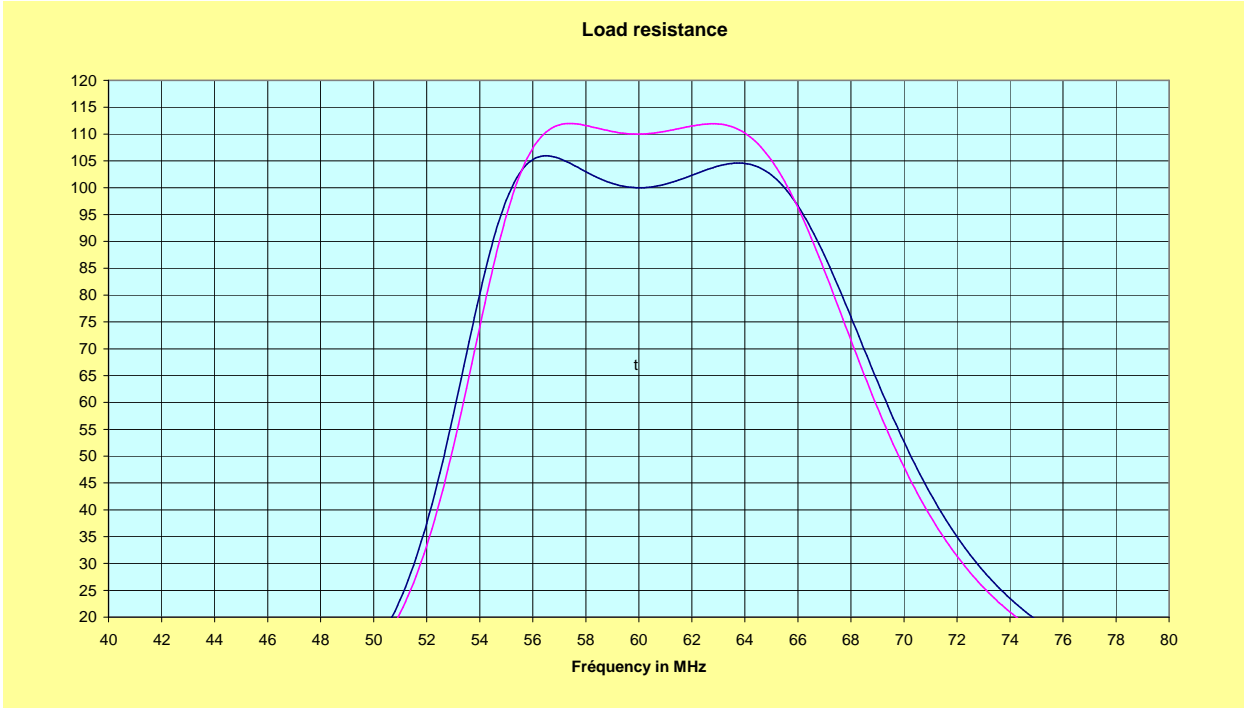


Annex 11 - Example of a RF circuit

$R_{reaload} = 50\Omega$



	Ohm	C2 pF	C3 pF	L2 nH	Ck pF	L1 nH	C1 pF
R_{I1}	100	68.48	68.06	58.00	29.66	54.27	100
R_{I2}	110	75.03	74.80	55.50	29.20	54.45	100



RF Bandwidth